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An engineered resupply system for Humanitarian Assistance and Disaster Relief operations

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THESIS

AN ENGINEERED RESUPPLY SYSTEM FOR HUMANITARIAN ASSISTANCE AND DISASTER RELIEF OPERATIONS

by

Wei Sheng Jeremy Kang

September 2017

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This research examines the effectiveness of resupply systems in humanitarian assistance and disaster relief (HADR) operations by exploring different permutations of operational energy (OE)-focused assets and policies that a Marine Expeditionary Unit (MEU) employs to improve its throughput of resources to disaster victims. The basis for the modeled scenario is the support provided by the 31st MEU to the city of Hachinohe as part of Operation TOMODACHI. This thesis focuses on OE and only considers the medium tactical vehicle replacement (MTVR) as the baseline capability. An agent-based simulation is then used to model the effectiveness of OE-focused resupply strategies and capabilities. These options include (1) efficient driving techniques, (2) reducing idling time, (3) hybrid technologies, and (4) follower vehicles. To investigate their effectiveness, this research uses a design of experiments approach to efficiently examine a set of design factors for specified operational plans. Statistical results indicate that the operational plans employing shorter and quicker vehicle convoys that communicate with one another are most effective in resupplying isolated victims. This research also confirms that the employment of OE-focused assets and policies is effective in increasing timeliness of resupply. Taken together, these factors contribute toward increasing the operational reach of a MEU conducting HADR resupply.

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AN ENGINEERED RESUPPLY SYSTEM FOR HUMANITARIAN ASSISTANCE AND DISASTER RELIEF OPERATIONS

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ABSTRACT

This research examines the effectiveness of resupply systems in humanitarian assistance and disaster relief (HADR) operations by exploring different permutations of operational energy (OE)-focused assets and policies that a Marine Expeditionary Unit (MEU) employs to improve its throughput of resources to disaster victims. The basis for the modeled scenario is the support provided by the 31st MEU to the city of Hachinohe as part of Operation TOMODACHI. This thesis focuses on OE and only considers the medium tactical vehicle replacement (MTVR) as the baseline capability. An agent-based simulation is then used to model the effectiveness of OE-focused resupply strategies and capabilities. These options include (1) efficient driving techniques, (2) reducing idling time, (3) hybrid technologies, and (4) follower vehicles. To investigate their effectiveness, this research uses a design of experiments approach to efficiently examine a set of design factors for specified operational plans. Statistical results indicate that the operational plans employing shorter and quicker vehicle convoys that communicate with one another are most effective in resupplying isolated victims. This research also confirms that the employment of OE-focused assets and policies is effective in increasing timeliness of resupply. Taken together, these factors contribute toward increasing the operational reach of a MEU conducting HADR resupply.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACE	air combat element
CONOPS	concept of operations
DDT	dynamic distribution team
DOD	Department of Defense
DOE	design of experiments
E2O	Expeditionary Energy Office
ESG	Expeditionary Strike Group
GCE	ground combat element
HADR	humanitarian assistance and disaster response
HAST	humanitarian assistance survey team
HHQ	higher headquarters
ITX	integrated training exercise
JFCOM	Joint Forces Command
LDC	local distribution center
LIB	less is better
MAGTF	Marine air-ground task force
MANA	map-aware non-uniform automata
MANA-V	map-aware non-uniform automata – vector
MCAGCC	Marine Corps air-ground combat center
MEB	Marine expeditionary brigade
MEF	Marine Expeditionary Force
MEU	Marine Expeditionary Unit
MIB	more is better
MOE	measure of effectiveness
MOP	measure of performance
MPEM	Marine air-ground task force Power and Energy Model
MPG	miles per gallon
MPH	miles per hour
MSBSE	modeling- and simulation-based systems engineering
MSSG	MEU service support group

MTVR	medium tactical vehicle replacement
NGO	non-governmental organization
NOB	nearly orthogonal-and-balanced
NOLH	nearly orthogonal Latin hypercube
NPS	Naval Postgraduate School
OE	operational energy
ONR	Office of Naval Research
PACOM	Pacific Command
PCC	pre-combat check
PDT&E	preliminary design test & evaluation
SE	systems engineering
SOP	standard operating procedures
TTP	tactics, techniques, and procedures
UGS	unmanned ground system
USFJ	United States Forces Japan
USMC	United States Marine Corps
USN	United States Navy

EXECUTIVE SUMMARY

Given the increased frequency and scale of natural and manmade disasters, militaries around the world have also been increasingly deployed in humanitarian assistance and disaster relief (HADR) operations due to their diverse range of logistics and medical equipment as well as their ability to deploy rapidly. Military units may not be ideally structured to respond to disasters, however; their effectiveness may also be limited by the operational reach of the delivery units and assets that they employ. The purpose of this research is to gain insights into the feasible operational energy (OE)-focused capabilities, tactics, techniques, and procedures (TTP) that a Marine expeditionary unit (MEU) may employ in order to extend its operational reach in the context of a HADR resupply operation. This thesis identifies the considerations and risks that a MEU commander may take into account in planning for a HADR resupply operation.

This thesis utilizes a large-scale design of experiments (DOE) applied to an agent-based simulation tool called the map-aware, non-uniform automata (MANA) to investigate the effectiveness of OE technologies and concepts (e.g., efficient driving techniques, hybrid technologies, and follower vehicles) in allowing the MEU to search for and resupply as many isolated victims as possible in a HADR scenario. This summary provides an overview of (1) HADR operations, (2) the model operating scenario used in this thesis, (3) the research methodology, and (4) the analytical results. The research in this thesis is aimed at guiding the implementation of OE-focused assets in HADR operations. In doing so, this research addresses the following questions:

1. What is the effectiveness of current MEU assets supporting HADR resupply operations in terms of throughput of resources?
2. How do the energy requirements of current MEU assets supporting HADR resupply operations limit the capability to maximize delivery of resources to disaster areas?
3. How do OE considerations influence the resupply options of a MEU conducting HADR resupply operations?

4. What OE-focused assets and behaviors should a MEU include in its resupply system to improve its throughput of resources to disaster areas?

The Expeditionary Energy Office (E2O) is interested in understanding energy-based risk and the extent to which energy demand impacts operational capabilities (Marine Corps Expeditionary Energy Office 2016). This involves an analysis of current capabilities in meeting mission requirements, as well as the employment of enhanced OE-focused assets and TTPs in extending operational reach. Metrics obtained from this research will help E2O to develop a better understanding of the energy demand and organic logistic capabilities of a MEU conducting resupply operations to isolated victims in a HADR scenario.

This research focuses on the support provided by the 31st MEU to the city of Hachinohe as part of Operation TOMODACHI, using it as the operational scenario in this study. In particular, this thesis studies the land-based resupply operations to assist isolated victims. The concealment and positioning of the isolated victims influence the logistical demand on the MEU. To answer the research questions, three measures of effectiveness (MOEs) are identified: (1) throughput of relief supplies to isolated victims, (2) timeliness in delivering relief supplies to isolated victims, and (3) fuel efficiency of each capability instantiation. These MOEs are quantifiable and relevant to the research topic and are direct measurements of the success of a HADR resupply operation.

The operational scenario is incorporated in MANA, and the resulting MANA model mimics the interactions between local distribution centers (LDCs), dynamic distribution teams (DDTs), and isolated victims. These interactions provide insights into the efficiency and effectiveness of the resupply capabilities of the MEU. A snapshot of the MANA simulation model is shown in Figure 1, with LDCs in blue “plus” icons, DDTs in blue truck icons, and isolated victims in red human icons.

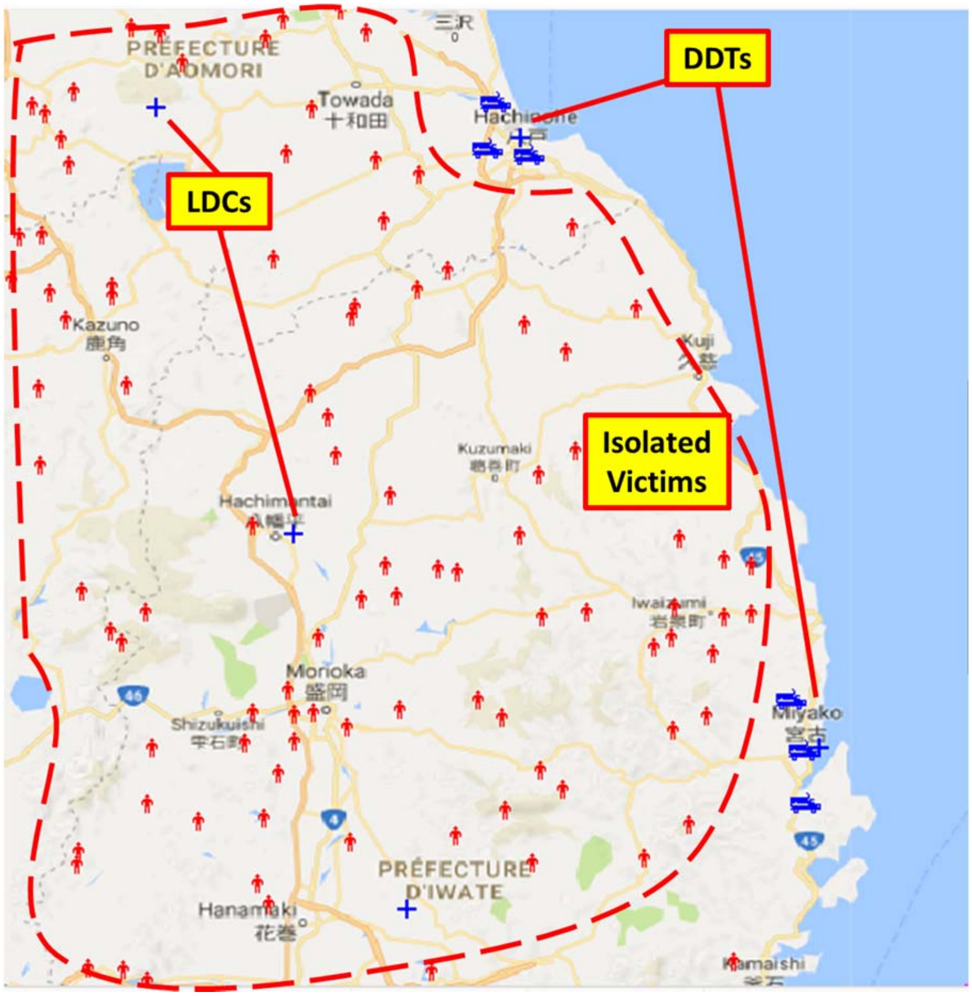

Figure 1. Snapshot of the MANA Simulation Model. Adapted from Google Maps.

A design of experiment (DOE) approach is used to explore extensively the problem space in a systematic and efficient manner. In particular, the nearly orthogonal-and-balanced (NOB) design technique was utilized to generate a 256-design-point matrix for the eight design factors used in this thesis. Decision factors used were: (1) operational plan, (2) reduce idle time, (3) fuel efficiency, and (4) communication devices. Noise factors used were concealment and trafficability.

This study utilized both arithmetic calculations and two phases of experimentation. Mathematical calculations were first performed to obtain several analytical solutions in order to determine the plausibility of the simulation results. The first phase of experimentation utilized 40 replications per design point to quickly screen out dominant factors, while the second phase of experimentation utilized 100 replications per design point to generate data for subsequent analysis. Data farming techniques were used to vary the input parameters in a systematic manner throughout the simulation runs. The resulting data sets were then analyzed statistically to reveal any interesting patterns, clusters, or outliers from the interactions between the design factors in the simulation.

The analyzed results of this thesis provide the E2O insights into which OE-focused assets or policies contribute most toward the effective delivery of relief supplies to disaster victims, and help guide the E2O in the implementation of OE-focused assets in HADR operations. Specific findings from this study include: (1) fuel allocated to the ground combat element (GCE) of the MEU may not be sufficient to support the energy requirements of the fleet of MTVRs in conducting HADR ground resupply operations; MEU commanders may have to reallocate fuel designated for other elements, such as the air combat element (ACE) or the MEU service support group (MSSG) to support the HADR resupply operation, and (2) choice of operational plan and use of communication devices greatly influence the throughput of relief supplies. In terms of OE-focused assets and policies, this research confirms the employment of: (1) trained drivers, (2) hybrid technologies, and (3) follower vehicle technologies as the most effective measures toward increasing timeliness in delivering relief supplies. Taken together, these factors contribute toward increasing the operational reach of a MEU conducting HADR resupply operations in terms of number of victims resupplied and time taken to resupply victims.

Reference

Marine Corps Expeditionary Energy Office. 2016. "Expeditionary Energy Office Research Focus Areas." PowerPoint presentation, Headquarters United States Marine Corps. Last modified November 16.

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trying, especially after what had happened, and I cannot adequately articulate my love and the respect that I have for you.

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I. INTRODUCTION

A. PURPOSE

This study provides the United States Marine Corps (USMC) with insights about alternate options for incorporating operational energy (OE)-focused assets to improve its baseline resupply configuration in certain scenarios. Operational energy is defined as “the energy required for training, moving, and sustaining military forces and weapon platforms for military operations” (USMC Expeditionary Energy Office 2011, 18). The result of this study will provide insights into the employment of new technologies and concepts in OE such as efficient driving techniques, hybrid technology, and autonomous vehicles, in enhancing resupply operations in humanitarian assistance and disaster relief (HADR) scenarios. This thesis also explores how a Marine expeditionary unit (MEU) may develop and employ an appropriate concept of operations (CONOPS) to allocate its resources more effectively and optimize its operations.

B. BACKGROUND AND MOTIVATION

With natural and manmade disasters increasing both in frequency and in scale, there is a greater demand for militaries to provide HADR (McMillen 2007). Militaries are not ideally structured to respond to disasters, however. While most conventional military operations are conducted only after detailed planning and usually during a period of heightened tensions, disasters can happen at any time or place. Military doctrine for HADR operations is not yet fully formed; deliverables of the mission, scope of operations, and coordination with or transition to civilian organizations are mainly ad hoc. The inherent complexity of HADR operations is also increased with the involvement of non-military organizations (Greenfield and Ingram 2011). Lastly, the effectiveness of a MEU supporting HADR operations is limited by the operational reach of the delivery units and the assets that it employs, as the supplies carried by the MEU may not specifically be configured for HADR missions (Webb 2006). To this end, commanders believe that the limitation of operational reach can be alleviated with OE-focused assets and behaviors (Department of Defense 2016, 15). Here, we define OE-focused assets and behaviors as those designed to reduce energy usage or self-generate power.

In the systems engineering (SE) process, the need to extend operational reach translates to a stakeholder requirement that must be addressed. In the context of HADR missions, militaries are essentially conducting logistics operations (Greenfield and Ingram 2011); HADR operations frequently involve the distribution of aid and supplies, transportation of relief workers and disaster victims, construction of temporary shelters, and administration of medical treatment. Hence, there is a need to study if and how the implementation of OE-focused assets and behaviors is able to improve the operational reach of a resupply system for HADR operations. This thesis will attempt to answer the main research question: Given a HADR operation, how should a MEU engineer its resupply system to render aid to disaster-struck locations more effectively?

C. SURVEY OF RECENT STUDIES

A survey of past studies on energy consumption during military operations, and analysis of various HADR operations, provided the academic context to this thesis' focus on the implementation of OE-focused assets and behaviors in supporting HADR operations.

Besser et al. (2013) examined methods to reduce the logistical footprint of a MEU (e.g., fuel usage, manpower, and amphibious systems) to maximize the delivery of water and other supplies during HADR operations. Indeed, their results showed that significant improvements were possible through the local production of water and the use of autonomous vehicles. In addition, the employment of hybrid and follower vehicles also showed some potential to reduce fuel usage in certain mission areas, subject to certain constraints (Besser et al. 2013).

Peters (2016) identified behavioral trends that can be changed through "training and education, policy and planning, and leadership and communication, to improve individual and organizational awareness of the importance of efficient and effective energy use," in order to achieve energy savings (Peters 2016, xvi). Hill and Simoncini

(2015) also investigated the costs of vehicle idling in the military, and concluded that huge savings of over $40M could be achieved by reducing vehicle idling time. In particular, there are opportunities to achieve increased operational reach, among others, through the improved use of generators, environmental control units, and vehicles.

Alexander et al. (2011) employed an SE methodology to explore the "requirements to provide assistance in the form of goods and services" (Alexander et al. 2011, vii) in the immediate 60 days of a flooding disaster to a fictional country in Africa. The scope of the study included constructing and analyzing alternate architectures in order to investigate the effectiveness of a sea-based aid distribution point, and to "better understand and possibly improve upon the delivery tactics and methods of delivery associated with HADR operations" (Alexander et al. 2011, 153).

In the domain of modeling and simulation, Hinkson (2010) developed a map-aware non-uniform automata (MANA) simulation model to "evaluate the logistical impact of enhanced company operations on a MEU" (Hinkson 2010, v). This research utilized a design of experiment technique called the "nearly orthogonal Latin hypercube (NOLH) to vary a set of design factors in an efficient manner" (Hinkson 2010, v). The use of MANA and the NOLH design can also be modified to explore the resupply system of a MEU supporting HADR operations. Similarly, Besser et al. (2013) and Alexander et al. (2011) constructed simulation models using ExtendSim and SimKit software to study the operational reach and throughput of resupply systems in HADR operations by varying the type/use of vehicles and other OE-focused assets.

D. DEFINITION OF RESUPPLY SYSTEMS

As the resupply system for a HADR operation may differ from the resupply system for other type of operations, it is necessary to define the logistical flow of relief supplies for a HADR operation. For such operations, relief supplies are gathered from international and regional sources, and they are sent to the affected country by air, sea, and ground transportation. In the affected country, these relief supplies are typically stored in depots for customs clearance and inspection before they are routed downstream to local distribution centers (LDCs), which are forward-positioned warehouses set up closer to the scene of the disaster to provide more responsive resupply. From the LDCs, military forces and non-governmental organizations (NGOs) are usually charged with the allocation and distribution of relief supplies to their intended beneficiaries. Here, we focus our study of HADR operations on the "last mile" distribution of supplies from LDCs to disaster victims. In particular, this thesis considers a resupply system that utilizes military ground-based vehicles to distribute relief supplies stored in LDCs to victims who have been displaced and isolated by a disaster. A typical resupply system for large-scale HADR operations involving international and military actors is shown in Figure 1. We highlight the scope of this thesis in the red box, and define it in SE terms.

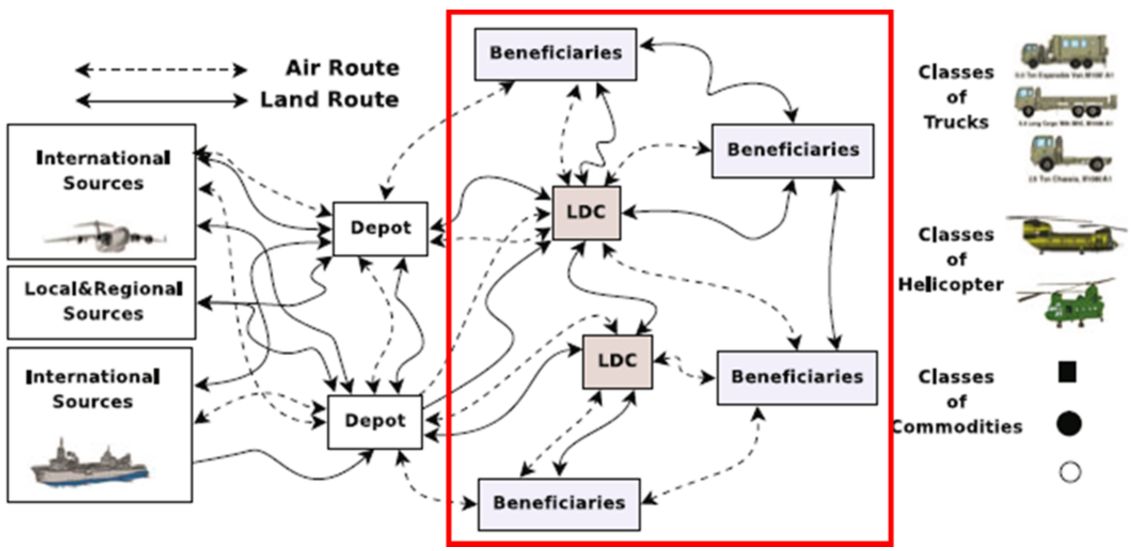

Figure 1. A Typical Resupply System for HADR Operations. Adapted from Balcik, Beamon and Smilowitz .

Following the SE process, a system's context diagram defines the boundaries of a system in order to distinguish it from the environment. According to Kossiakoff et al. (2011, 266), the objective of a systems context diagram is "to focus attention on external factors and events that should be considered in developing a complete set of system requirements and constraints"; it provides for a structured and systematic approach in defining the MEU resupply system to be studied in this thesis. The systems context diagram, using an input-output model, for a MEU resupply system is shown in Figure 2. External sources of inputs to the HADR resupply system include: (1) international sources, (2) local and regional sources, (3) the DOD, and (4) the environment. International, local, and regional sources provide the necessary relief supplies to the MEU for distribution. The DOD gives the MEU its mission orders and stipulates the CONOPS that the MEU resupply system has to utilize. Lastly, the environment, which consists of destroyed or degraded roads and unpredictable weather, affects the manner in which the MEU operates and the assets that it may employ. In turn, the MEU resupply system affects: (1) disaster victims, and (2) the U.S. government. Firstly, disaster victims are direct recipients of the relief supplies distributed by the MEU resupply system. Secondly, the success or failure of the MEU resupply mission may affect the image of the U.S. as a country, or of the U.S. government.

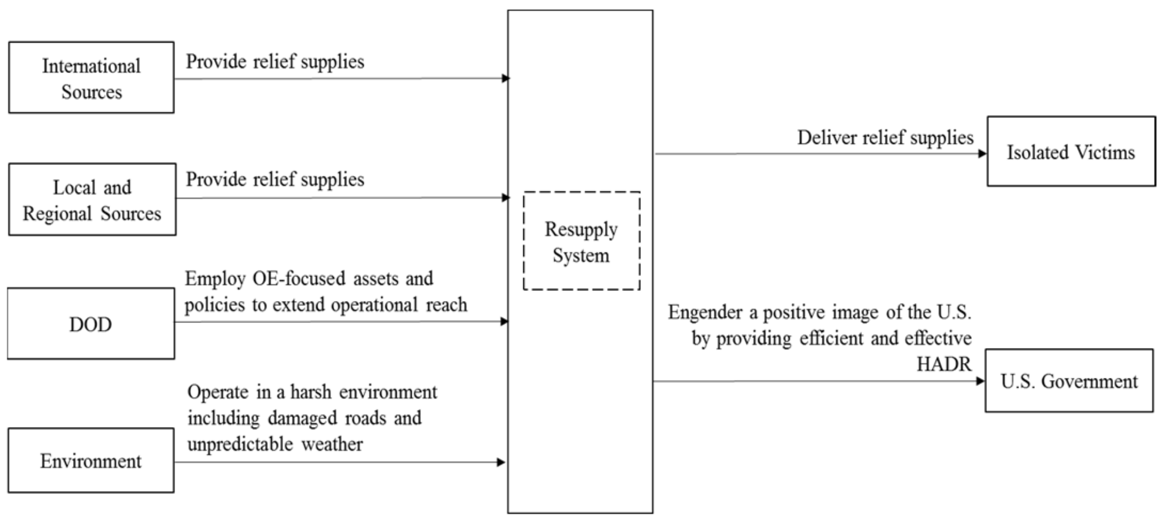

Figure 2. Systems Context Diagram for a MEU Resupply System.

E. TYPES OF DISTRIBUTION MODELS

1. Direct Point-to-Point

In this model, relief items are delivered from the donor country to the disaster victims directly. For urgent and unanticipated operations such as HADR, the advantage of a point-to-point method is that disaster victims may receive the relief supplies more quickly. The drawbacks are that a large amount of manpower is required to deliver all relief supplies individually to all disaster victims, and multiple trips may be necessary to deliver different types of relief supplies if there is no sorting and packaging done prior to distribution, resulting in piecemeal delivery.

2. Hub-and-Spoke

In the hub-and-spoke model, relief items are delivered to one or several LDCs in the affected country. Different relief items are sorted and packaged at the LDCs before distribution to the disaster victims. Military forces and local NGOs will collect the relief supplies at these hubs and distribute them to the disaster victims. The advantage of the hub-and-spoke system is that it is more efficient, and disaster victims are able to receive different types of relief supplies simultaneously. The addition of an extra stop at the hub means that relief supplies will take more time to reach the disaster victims, however. The hub-and-spoke model will be adopted as the distribution model in this thesis.

3. Push

In the push distribution model, the MEU's higher headquarters (HHQ) makes projections of what the disaster victims will require and delivers relief items based on those projections. Relief items are then distributed to or near the victims' actual geographical location. From an OE-viewpoint, the push distribution model is more resource intensive for the military forces and local NGOs tasked with the distribution operation as it requires the transportation of relief items from the LDCs to the disaster victims. It may be a necessary strategy; however, as certain disaster victims may be immobile or would encounter great difficulty in moving to LDCs. The push distribution model is used in this thesis as the amount of relief items carried by each dynamic distribution team (DDT) convoy is based on the HHQ's projection, rather than on actual demand. In addition, the relief supplies are delivered to or near the disaster victims.

4. Pull

In the pull distribution model, the MEU HHQ is responsible to track disaster victims' demand of relief items and deliver based on actual demand. At the same time, disaster victims are required to collect relief supplies from the LDCs. As the only energy expended in this model is in the operation of the LDCs, it is also considered less resource intensive. The pull distribution model may only be employed for small areas or in areas where mobility is not a concern, however; disaster victims may also be unable to communicate their demands directly with the MEU HHQ. Hence, the pull distribution model may not be practicable in most HADR operations.

F. RESEARCH QUESTIONS

By refining the identified areas of improvement, we restate the main research question: How should a MEU engineer its resupply system to render aid to disaster-struck locations more effectively? Specifically, this research will address the following questions:

1. What is the effectiveness of current MEU assets supporting HADR resupply operations in terms of throughput of resources?
2. How do the energy requirements of current MEU assets supporting HADR resupply operations limit its capability to maximize delivery of resources to disaster areas?
3. How do OE considerations influence the resupply options of a MEU conducting HADR resupply operations?
4. What OE-focused assets and policies should a MEU include in its resupply system to improve its throughput of resources to disaster areas?

G. POTENTIAL AREAS OF IMPROVEMENT

The military's distribution capability in the form of airlift, sealift, and ground transportation are its most ready and relevant capabilities for employment in HADR missions (Webb 2006). Given that resupply requirements are ground-driven and demand-generated with short response lead times, it is difficult to perform deliberate planning for resupply missions in a HADR scenario. As the destruction of critical infrastructure is a common occurrence in natural disasters, the MEU tasked with conducting HADR operations must be prepared to be self-reliant in terms of energy. In this thesis, a MEU is tasked with searching for and transporting HADR supplies from LDCs to victims who may have been geographically isolated by the disaster. The MEU commander is concerned with the ability to transport and distribute supplies to as many disaster victims as possible, but must also consider the limited energy supplies that are available to the MEU; energy-efficient means must be explored and employed as far as reasonably practicable. Hence, the potential areas of improvement explored in this thesis are:

1. Can the MEU locate isolated victims, and upon doing so, deliver adequate resupply to them?

2. How much energy is required to carry out the resupply missions?

3. How can the MEU be more energy-efficient in HADR operations?

H. BENEFITS OF THE STUDY

This study provides the Marine Corps with insights into alternate structures and CONOPS that incorporate OE-focused assets and policies that are better suited for HADR scenarios than its baseline configuration. The result of this study will form the basis for determining the feasibility of implementing OE-focused technologies and concepts such as smart power grid management, efficient driving techniques, and hybrid/autonomous vehicles, in enhancing resupply operations in HADR scenarios. This thesis considers how the MEU may develop and employ appropriate OE-focused assets/behaviors and CONOPS to allocate its resources more effectively and improve its efficacy in HADR operations.

I. SCOPE OF STUDY

This study is a modeling- and simulation-based systems engineering (MSBSE) effort that will provide insights into the impact of employing OE-focused assets and policies in HADR operations. The intent is not to provide quantitative judgement on the amount of improvement that can be achieved through the implementation of these OE-focused assets and CONOPS. This study employs computer simulation to address topics that cannot be solved analytically, such as the uncertainties and randomness involved in HADR operations. The dispersal of victims, difficulty in locating victims, and influx of donated relief supplies are just some of the elements of HADR operations in which a MSBSE approach is useful. Additionally, simulation is ideal for obtaining insights and drawing inferences from new processes or procedures, such as the incorporation of OE-focused assets/behaviors and CONOPS in HADR operations to extend operational reach (P. J. Sanchez 2007).

The first step in constructing the model is to define the system of interest (SOI) (P. J. Sanchez 2007). Wasson (2006, 81) defines SOI as “the system of a mission system and its support system(s) assigned to perform a specific organizational mission and accomplish performance-based objective(s) within a specified time frame.” As depicted in Chapter I, Section D, Figure 1, the SOI in this study is the resupply system of the MEU. The supporting systems include the LDCs, vehicle delivery systems, beneficiaries (disaster victims), and CONOPS used to employ the assets.

The SOI relationship diagram of the resupply system of the MEU is depicted in Figure 3, which illustrates the different systems that are closely related and interact together in the context of the MEU resupply system. Thus, it is important that the design of any system in the MEU resupply system must consider all possible impacts that it will effect on other systems, as well as the possible impacts that other systems may have on it. These impacts may propagate horizontally to affect peer systems that share the same capabilities, or cascade vertically upward or downward to affect higher or subordinate systems.

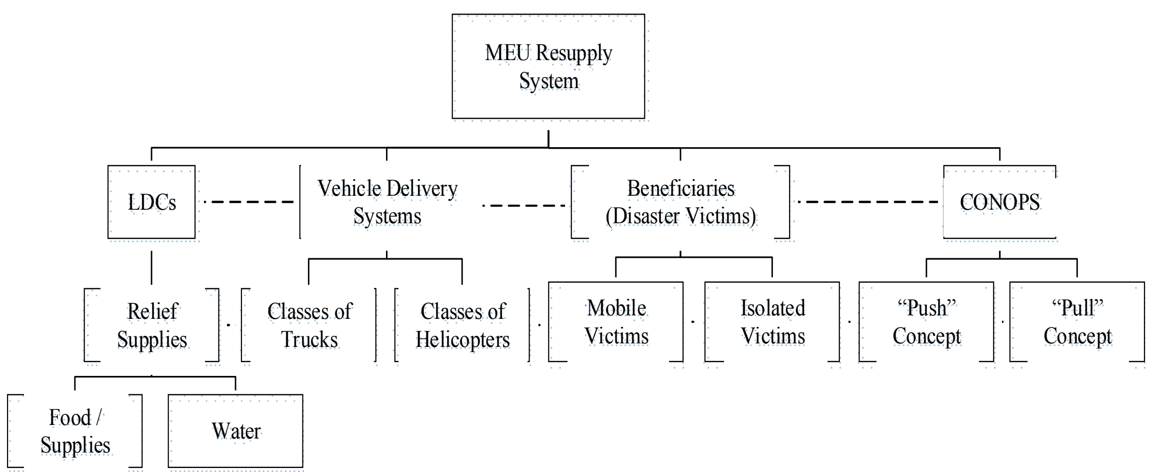

Figure 3. SOI Relationship Diagram.

The first part of this thesis will utilize an SE process to identify the: (1) operational need, (2) system requirements, and (3) system functions of a resupply system in a HADR operation. From these, system alternatives will be generated through the addition of OE-focused assets and employment of different CONOPS; instantiations of feasible combinations shall be proposed. In the second part of this thesis, a constructed simulation model will be used to assess the OE performance of the proposed instantiations in order to provide insights into the potential tradeoffs, as well as generate data for the analysis and comparison of the various instantiations, to guide future implementation. To illustrate, the "Vee" model for the SE process is shown in Figure 4. The scope of this thesis will address the: (1) requirements and (2) design in the left-hand side of the "Vee" model; modeling and simulation techniques will be utilized to investigate the effectiveness of the detailed designs in meeting the stated requirements and architecture before the implementation phase, and can be considered to be a preliminary developmental test and evaluation (PDT&E) for the MEU resupply system. The results of the PDT&E will in turn provide insights that refine the design.

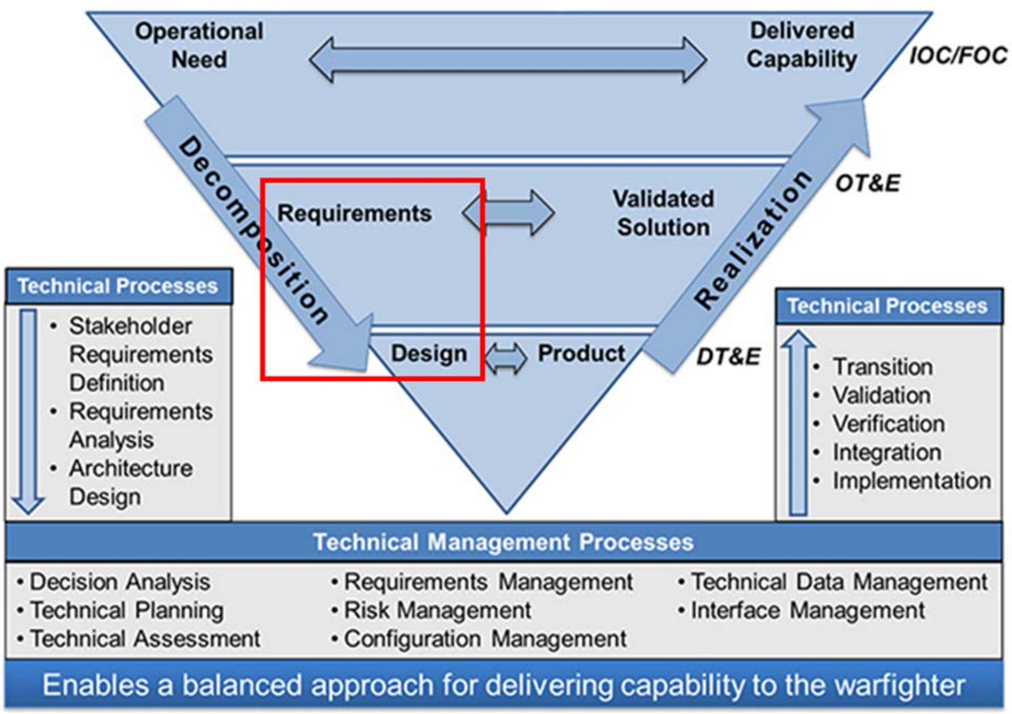

Figure 4. Systems Engineering "Vee" Model. Adapted from Defense Acquisition University.

The proposed OE-focused assets and policies that are used in this study were provided by the USMC Expeditionary Energy Office (E2O), Headquarters Marine Corps, and theses by Besser et al. (2013) and Peters (2016). These include the employment of efficient driving techniques, autonomous vehicles, and reducing idling time, among others. On the other hand, the proposed CONOPS were derived from varying: (1) the type of resupply model (e.g., push or pull) and (2) the flexibility that a resupply team is given to resupply disaster victims as compared to being compelled to stay on its assigned search and delivery route. Using these design factors, a design of experiments (DOE) approach is adopted to explore the experimental space and thereby understand the impact of the design factors on key measures of effectiveness (MOEs).

This study focuses on the "last mile" resupply of relief supplies such as food, water, and comfort items from LDCs to isolated victims. As one of the aims of this study is to minimize the amount of OE used to fulfill HADR resupply demands, only ground-based assets are considered in the following analysis, as they are more energy efficient than air assets (Besser et al. 2013). In addition, ground-based assets are also more feasible in responding to the relatively small operation area (100mi by 60mi) used in this study. Specific MOEs include: (1) the proportion of victims resupplied, (2) the time taken to resupply these victims, and (3) the total number of resupply trips.

J. THESIS ORGANIZATION

The remaining chapters in this thesis are organized in the following manner. Chapter II presents a review of the related academic studies that have been conducted regarding resupply systems in HADR operations. Chapter III details the operational scenario used in this study as well as the considerations and assumptions used in the development of the MANA simulation model. This model will be subsequently used to assess the effectiveness of different OE-focused instantiations. Chapter IV goes through the development of the MANA simulation model and the simulation runs. Chapter V presents the results and analysis of the simulation runs. Finally, Chapter VI provides the insights and recommendations for OE-focused assets or policies that contribute most toward the effective delivery of relief supplies to disaster victims.

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II. ACADEMIC CONTEXT

A. LITERATURE SURVEY

An extensive literature review of the force structure and CONOPS of a MEU, U.S. Department of Defense (DOD) OE initiatives, MEU force capabilities, and HADR operations was conducted to better understand the area of research. The relevant portions are highlighted below.

For greater details regarding the force structure and CONOPS of a MEU, the following military doctrines and documents were consulted. First, the Marine Air Ground Task Force (MAGTF) Logistics Planning Factors Study was used as a planning guide for the capabilities and resources that a notional MEU would deploy for a HADR operation. Secondly, the document Expeditionary Force 21: Forward and Ready Now and in the Future (2014) was referred to as a guide for how the USMC "will be postured, organized, trained, and equipped to fulfill assigned public law and national policy responsibilities" (Headquarters USMC 2014, 5). Thirdly, the USMC Expeditionary Energy Strategy and Implementation Plan (2011) was consulted to understand the expeditionary energy goals and initiatives/policies designed to meet these goals. Finally, the U.S. Department of Defense (DOD) 2016 OE Strategy document was studied to understand how the DOD plans to implement OE-focused initiatives in resupply operations.

For analysis of HADR operations, there has been an increase in studies pertaining to this field as the quantity and severity of natural or man-made disasters have increased over the years. With particular reference to the study of resupply systems in HADR operations, Bergeron (2011) examines the force capabilities necessary to support HADR operations. He distills the 10 equipment capabilities essential for HADR operations, and he concludes that eight out of these 10 capabilities contribute toward the effectiveness of the resupply system, recognizing the main role that logistics plays in HADR operations. Menhart (2015) analyzes the effectiveness of prepositioned stocks toward HADR operations. He argues that with a shorter supply chain, militaries are able to respond more swiftly and sustain their missions for longer periods by not having to load and transport large amounts of supplies not only across oceans and continents, but also across land. Moroney et al. (2013) outline the various capabilities and resources that the U.S. military can deploy for HADR operations. Indeed, given their inherent capability, flexibility, and adaptability to accomplish a full spectrum of operations, including operations-other-than-war, MEUs are particularly suitable to be deployed for HADR missions. Wolf (2003) stated that given the U.S.'s status as provider in times of crisis and the expeditionary posture of the Marine Corps, it is without doubt that the USMC will continue to be called on in the future to support HADR missions that are caused by tsunamis, hurricanes and earthquakes.

B. MEU STRUCTURE AND CAPABILITIES

The MEU is "a MAGTF constructed around a reinforced infantry battalion, a reinforced helicopter squadron, and a task-organized organized logistics combat element. It normally fulfills the Marine Corps' forward sea-based deployment requirements. The MEU provides an immediate reaction capability for crisis response and is capable of limited combat operations" (USMC Expeditionary Energy Office 2011, 82). Given their inherent capability, flexibility, and adaptability to accomplish a full spectrum of operations, including operations-other-than-war, MEUs have traditionally been called upon to provide HADR to countries and areas that have been devastated by natural calamities and man-made catastrophes; at least three MEUs are actively deployed around the world at any given time to respond to any unexpected threats or disasters (Gastrock and Iturriaga 2013). To carry out its missions, the MEU is comprised of: (1) a command element, (2) a ground combat element, (3) an aviation combat element, (4) a logistics combat element, and (5) a Marine special operations company. The structure of a notional MEU is illustrated in Table 1.

Table 1. Structure of a Notional MEU. Source: Department of the Navy (2009, 1-1).

Element	COMMAND ELEMENT (CE)	GROUND COMBAT ELEMENT (GCE)	AVIATION COMBAT ELEMENT (ACE)	LOGISTICS COMBAT ELEMENT (LCE)	MARINE SPECIAL OPERATION COMPANY (MSOC)
	MEU/MEU (SOC) command and control is provided by the Command Element	The GCE is structured around a reinforced infantry battalion	The ACE is a composite/reinforced squadron structured around Medium Lift or Tilt-Rotor Squadron	The LCE is structured around Combat Logistic Battalion (CLB) provides the following	The MSOC is a special operations force partnered with the MEU/ARG for training and deployment
Personnel	Approximately 169 personnel: USMC: 25 OFF and 140 ENL, USN: 1 OFF and 3 ENL	Approximately 1200 personnel: USMC: 59 OFF and 1086 ENL, USN: 3 OFF and 50 ENL	Approximately 417 personnel: USMC: 75 OFF and 337 ENL, USN: 1 OFF and 4 ENL	Approximately 273 personnel: USMC: 14 OFF and 232 ENL, USN: 6 OFF and 21 ENL	Approximately 84 personnel: USMC: 8 OFF and 69 ENL, USN: 7 ENL
Comprised of	MEU/MEU (SOC) commander and staff	H&S Company	Medium Lift or Tilt-Rotor Squadron	Headquarters and Service Platoon	Company HQ
	Imagery Interpretation Det	Rifle Company x3	Heavy Helicopter Squadron Det	Communications Platoon	Marine Special Operations Teams (MSOT) x3
	Human Exploitation Team	Weapons Company	Light/Attack Helicopter Squadron Det	Maintenance Platoon	Enablers: Admin, EOD, Riggers, Maintenance, Supply, Ammo Techs, Fire Control Team, Embark
	Ground Sensor Det	Tank Platoon	Marine Attack Squadron Det	Supply Platoon	
	Topographic Det	Artillery Battery	Marine Fighter / Attack Squadron Det (Tethered)	Transportation Support Platoon (Includes Landing Support & Motor Transportation)	
	Radio Battalion Det	LAR Platoon/ Company	Marine Aerial Refueler/ Transport Squadron Det	Health Services Platoon	
	Communications Battalion Det	Shore Fire Control Party	Marine Air Control Group Det	Engineer Platoon	
	Force Reconnaissance Platoon	Combat Engineer platoon	Marine Wing Support Squadron Det		
	Military Police Squad	Division Reconnaissance Platoon	Marine Aviation Logistics Squadron Det		
		Assault Amphibian Vehicle Platoon			

To support a wide range of operations, the MEU carries with it a wide range of equipment. A sample list of baseline equipment that the MEU may carry aboard ship during deployment is detailed in Figure 5.

CE	BLT	ACE	LCE	MSOC
(1) MEWSS LAV	(7) LAVs	(12) CH-46E/MV-22B	(2) TWPS	(16) HMMWVs
(18) HMMWVs	(15) AAVs/EFVs	(4) CH-53E	(5) Refuelers	(4) Trailers
(1) JTF Enabler	(4) Tanks ***	(4) AH-1W	(1) M88A1	
(6) CRRCs*	(6) M777A2	(3) UH-1N/Y	(15) MTVRs	
	(20) CRRCs**	(6) AV-8B	(18) HMMWVs	
	(2) ACEs	(5) A-MANPADS	(1) AAVR7	
	(16) MTVRs	(5) HMMWVs	(1) 5k Forklift	
	(8) 81 MMs	(2) KC-130	(1) EBFL Forklift	
	(8) TOW Launchers	(6) F/A-18 *****	(1) D-7	
	(64) HMMWVs		(1) Excavator	
	(7) IFAVs		(2) TRAM Forklift	
	(6) M327 (EFSS) ****			

Note

CE	Command Element
BLT	Battalion Landing Team
ACE	Air Command Element
LCE	Logistics Combat Element
MSOC	Marine Special Operations Company
*	CONUS deploying MEUs embark (6) CRRCs.
**	31st MEU embark (20) CRRCs.
***	31st MEU does not embark.
****	The EFSS (120mm mortar) may be employed in place of the M777, in conjunction with the M777 (reduced numbers for both), or not at all.
*****	An F/A-18 Det could potentially be tethered to a MEU deployment.

Figure 5. Sample MEU Baseline Equipment. Source: USMC .

C. DEFINITION OF HADR OPERATIONS

Humanitarian assistance "consists of activities conducted to relieve or reduce human pain, disease, hunger, or deprivation created by conditions that might present a serious threat to life or that can result in great damage to or loss of property," while disaster relief "refers to the goods and services provided to meet the immediate needs of disaster-affected communities" (Multinational Planning Augmentation Team 2010, D-1 C-2).

In addition, the Naval Operations Concepts 2010 – Implementing the Maritime Strategy document "distinguishes between the requirement to conduct both 'Proactive' and 'Reactive' HADR missions" (Department of the Navy and U.S. Coast Guard 2010, 47–48). "'Proactive' HADR missions include regular engagement with foreign nations and NGOs to provide medical support, train first responders, and complete public works projects" (Bergeron 2011, 4–5), whereas "Reactive" HADR missions are the U.S. government's and military's response to a disaster that has already taken place. The aim of "Proactive" HADR missions is to increase the capability of the foreign nations and NGOs to deal with sudden unexpected disasters, while the aim of "Reactive" HADR missions is to reduce immediate human suffering. Regardless, these HADR missions allow the U.S. to generate goodwill and shape positive public perception of U.S. military and foreign policy. Unless otherwise stated, the HADR operations studied in this thesis refer to "Reactive" HADR missions, since military forces are typically deployed to assist in "Reactive" HADR missions rather than "Proactive" HADR missions.

D. RECENT HADR OPERATIONS

The USMC has participated in a wide range of HADR operations. Three case studies are presented in this thesis due to their recent, logistics-centric nature of operations for the USMC units involved, and due to the deployment of an entire MEU or larger MAGTF in each of these operations.

1. Operation TOMODACHI (Japan Earthquake and Tsunami)

A magnitude 8.9 earthquake struck mainland Japan on 11 March 2011 and triggered tsunamis that hit the north coast of Japan. The released tectonic force was so great that it shifted the floor of the Pacific Ocean by nearly 20 meters and unleashed seven tsunamis, the highest of which was as tall as 14–20 meters and reached as far as six miles inland. In total, the disaster killed almost 20,000 people, injured 5,270, and left almost 2,500 missing (Fire and Disaster Management Agency 2016). In addition, the tsunamis also caused the “catastrophic failure of the cooling system at the Fukushima nuclear power station, which led to the explosive meltdown of the nuclear reactor” (Gastrock and Iturriaga 2013, 21). Early assessments by the Japanese government indicated that even with the complete mobilization of their military and civil defense forces, Japan would not be able to deal with the disaster alone; external support from its allies was required to ensure a complete recovery (Wilson 2012). Thus, Operation TOMODACHI was stood up by the U.S. Forces Japan (USFJ), with assistance from U.S. Pacific Command (PACOM), to assist Japan in its time of need.

Among other things, the scope of Operation TOMODACHI included “radiological decontamination, humanitarian aid airlift/delivery and reception support, communication support, medical aid, search and rescue, and critical infrastructure recovery” (Gastrock and Iturriaga 2013, 52). The USMC participated mainly in transportation, search and rescue, and distribution of relief supply missions. In particular, the III Marine Expeditionary Force (MEF) was tasked to deliver supplies and clear access to affected areas (Moroney et al. 2013). Among other tasks, III MEF reconstructed the airport and various roads, cleared debris from schools for use as shelters, restored power, and delivered over “189 tons of food, 2 million gallons of water, and 87 tons of additional relief materials” (Wilson 2012, 17). In total, Operation TOMODACHI lasted 58 days from 12 March 2011 to 8 May 2011.

2. Operation UNIFIED RESPONSE (Haiti Earthquake)

A magnitude 7.0 earthquake stuck Haiti on 12 January 2010, which left approximately 220,000–316,000 dead and 300,000 injured (CNN 2016). The Joint Forces

Command (JFCOM) stood up Operation UNIFIED RESPONSE to provide HADR assistance to the devastated areas. II MEF deployed the 22nd and 24th MEUs, as part of Joint Task Force Haiti (JTF-H), to provide HADR support to Haiti.

> The task force focused efforts on establishing sea-based operations from which it could manage a hub-and-spoke-style distribution network of relief supplies. Initial and continuing guidance for the MEUs were to provide food, water, and critical medical aid to those affected by the disaster. This was evidenced through the U.S. Southern Command's mission to deploy assets to Haiti to conduct search and rescue operations, damage assessments, and transition to sustained HADR operations in order to prevent human suffering and additional loss of life. (Gastrock and Iturriaga 2013, 19)

The 24th MEU utilized MV-22 Osprey aircrafts to conduct aerial assessments of: (1) the damages inflicted by the earthquake, (2) infrastructure, and (2) the relief distribution capabilities in Haiti that were still functional. In terms of supply operations, the MEUs utilized their rotary-wing assets to distribute food and water supplies from the World Food Program Non-Governmental Organization (NGO) to 16 food distribution points for downstream distribution to Haitian victims (Gastrock and Iturriaga 2013). In total, 36 tons of emergency relief supplies were delivered through the MEUs (Cecchine et al. 2013). Operation UNIFIED RESPONSE was one of the longest U.S. military efforts in a foreign disaster relief operation, starting on 13 January 2010 and ending on 1 June 2010, a total of almost five months.

3. Operation SEA ANGEL II (Bangladesh Cyclone)

Cyclone Sidr ravaged Bangladesh on 15 November 2007. "More than 3,200 people were killed, an estimated 40,000 people were injured, and 1.6 million acres of farmland were destroyed" (Gastrock and Iturriaga 2013, 17). In response, the PACOM stood up Operation SEA ANGEL II to provide HADR for the unfortunate victims, and deployed the "Kearsarge Expeditionary Strike Group (ESG), the 22nd MEU, and a humanitarian assistance survey team (HAST) from the III MEF to assist in the relief operations" (Gastrock and Iturriaga 2013, 17).

As soon as the tasking order was given, Kearsarge and the 22nd MEU quickly began supply redistribution operations on 23 November 2007, utilizing their sea, air, and land assets. On land, "the third MEB provided aid in the following priorities: (1) water distribution and storage, (2) relief supplies distribution and transportation, and (3) preventive and primary medical care" (Gastrock and Iturriaga 2013, 18). These priorities were supported by the HAST's assessment on the ground and requests from the Government of Bangladesh.

> By 30 November 2007, they had delivered over 12,000 gallons of water and over 73,000 pounds of aid supplies. A majority of the water delivered initially was produced aboard Kearsarge, which had the capability to produce 200,000 gallons of potable water daily. Five-gallon collapsible bags were filled with the water, placed on pallets, and loaded onto aircrafts and ground transport vehicles for distribution. (GlobalSecurity 2013)

To increase the throughput of supplies to disaster victims, USMC leadership also proposed setting up a secondary LDC along the southeast coast. The government of Bangladesh did not accede to this request, however, and only one LDC was used throughout Operation SEA ANGEL II (Gastrock and Iturriaga 2013). In total, Operation SEA ANGEL II lasted 20 days from 18 November 2007 to 8 December 2007.

E. EXTENDING OPERATIONAL REACH

Salem and Gallenson (2014) studied the impact of human behavior on OE. They suggest that reducing expeditionary energy use may offer the opportunity to "extend reach, save lives, and utilize operational budgets wisely" (Salem and Gallenson 2014, 2). The first two benefits are directly applicable to a HADR resupply mission. They focused on the "behavioral aspect of the Marines' 'ethos change' to investigate the broad behavioral and attitudinal factors that may affect the overall efficient use of energy" (Salem and Gallenson 2014, 6–7). The authors used "ethnographic methods and Grounded Theory" (Salem and Gallenson 2014, 7) to collect data from actual Marines in actual operational environments to understand how their personal knowledge, attitudes, values, and motivations may vary according to different operational scenarios. In terms of convoy resupply operations, which is the main research topic of this thesis, they identify that "technology and ineffective policies and procedures have had the largest impact on efficient fuel use" (Salem and Gallenson 2014, 32); potential solutions should be targeted at improving these two factors.

Similarly, Peters (2016) explores the "factors that influence human behavior and negatively affect energy consumption in USMC ground units during operations" (Peters 2016, 2). He asserts that "improvements to equipment and the employment of renewable energy systems fail to address the impact that human behavior has on energy consumption" (Peters 2016, v); in particular, there exists:

> A huge opportunity in implementing a behavior-change strategy to improve individual and organizational awareness of the importance of efficient and effective use of energy. The proposed behavioral changes may result in: (1) improved energy security, (2) greater self-sufficiency, (3) increased operational reach, and (4) fewer casualties from the force protection of resupply convoys. (Peters 2016, 45)

This thesis recognizes the huge impact that human factors have on extending operational reach. Subsequently, enhancements to baseline capabilities shall include strategies aimed at changing operator attitudes and behavior toward OE usage.

F. MODELING HADR SCENARIOS

Analytical or optimization models seem to be more widely used to model HADR scenarios. Taniguchi and Thompson (2013) use a multi-objective optimization model to investigate the distribution of relief supplies to displaced victims in the city of Ishinomaki, Miyagi prefecture after the earthquake and tsunamis that struck Japan in 2011. The chosen objectives to be explored were: "(1) penalty of total shortage of supply, and (2) fuel consumption, as these objectives were determined to be the most critical for the distribution of relief supplies after a disaster" (Taniguchi and Thompson 2013, 208). Using a "multi-objective vehicle routing and scheduling problem" formulated by Okabayashi et al. (2011, I-887), Taniguchi and Thompson used the "elitist non-dominated sorting genetic algorithms method" to minimize the penalty of total shortage of supply and fuel consumption (Taniguchi and Thompson 2013, 210).

Simulation models have also been used to study HADR scenarios. For example, Wolf (2003) investigated the potential for using "agent-based models to support logistical decision-making in an urban HADR environment" (Wolf 2003, 2). To do so, he developed an agent-based model using MANA version 2.1 to investigate the effectiveness of a resupply convoy in distributing food to locals who have traveled to a couple of LDCs in an urban setting. Using data farming coupled with a Latin Hypercube design of experiments, Wolf was able to explore a very large data space in order to identify which input variables had the most effect on the mission success of distributing food. There were three entities in his model: (1) blue agents representing a convoy of relief supplies including a USMC security element, (2) yellow agents representing disaster victims who required aid, and (3) red agents representing "random harassing fire that could be encountered in a man-made humanitarian crisis such as a civil war" (Wolf 2003, 6). He concluded that the effectiveness of local communications was a critical factor in determining success, as it increased the squad awareness of the convoys to travel to potential locations of the disaster victims, and it also brought the disaster victims closer to the convoys once they knew that a convoy was nearby (Wolf 2003). Other simulation methods presented by Besser et al. (2013) and Alexander et al. (2011) used ExtendSim and SimKit software to study the operational reach and throughput of resupply systems in HADR operations by varying the type/use of vehicles and other OE-focused assets.

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III. METHODOLOGY

A. INTRODUCTION

This section describes the research methodology used in this thesis. First, an SE approach was used to identify the system functions of a resupply system in a HADR operation. We define different system configurations of OE-focused assets and CONOPS as alternatives for study. Second, open source and unclassified material was used to construct a notional HADR scenario that could be used to represent the last-mile delivery and distribution of relief supplies to isolated victims. This scenario was used to provide generalized insights into the interactions and potential tradeoffs between OE-focused assets, CONOPS, and operational reach in a HADR scenario.

B. FUNCTIONAL ANALYSIS FOR HADR OPERATIONS

In the SE process,

> functional analysis refers to an iterative process of translating system requirements into detailed design criteria and the subsequent identification of the resources required for system operation and support. It includes breaking requirements at the system level down to the subsystem, and as far down the hierarchical structure as necessary to identify input design criteria and / or constraints for the various elements of the system. The purpose is to develop the top-level system architecture, which deals with both "requirements" and "structure." (Blanchard and Fabrycky 2011, 86)

Functional analysis guides the formulation of system instantiations that will be studied in this thesis, as well as identifying the appropriate measures of effectiveness (MOEs).

In this aspect, HADR operations consist of "activities conducted to relieve or reduce human pain, disease, hunger, or deprivation created by conditions that might present a serious threat to life or that can result in great damage to or loss of property" (Multinational Planning Augmentation Team 2010, D-1 C-2), while disaster relief refers to the "goods and services provided to meet the immediate needs of disaster-affected communities" (Multinational Planning Augmentation Team 2010, D-1 C-2). To that end, the essential tasks in HADR operations include: "(1) information and knowledge management, (2) needs assessment, (3) supply, (4) deployment and distribution, (5) health service support, and (6) collaboration and governance" (Apte and Yoho 2012, 312). The top-level functional breakdown of Conduct HADR Operations is illustrated in Figure 6.

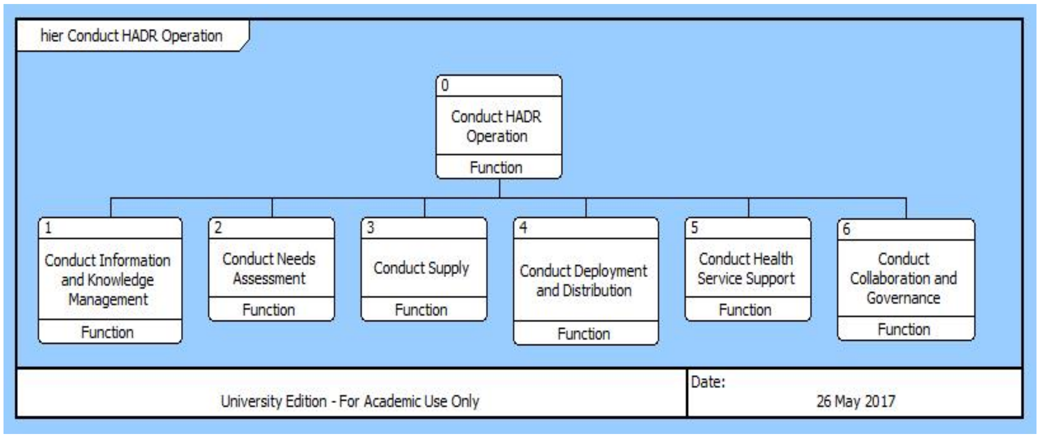

Figure 6. Top-Level Functional Hierarchy of HADR Operations. Adapted from Apte and Yoho (2012).

Conduct Information and Knowledge Management refers to the continuous collection, organization, and analysis of real-time information in order to prepare for needs assessment and operation planning. Conduct Needs Assessment refers to the determination of the scale of disaster destruction and the scope of disaster aid that must be delivered to provide relevant and timely relief. Conduct Supply refers to the procurement, warehousing, and managing of relief supplies. Conduct Deployment and Distribution refers to the transport and distribution from their storage locations to their point of consumption. Conduct Health Service Support refers to the provision of medical aid. Lastly, Conduct Collaboration and Governance refers to the partnership between all HADR stakeholders and related security operations for the HADR operation to be conducted in an effective and efficient manner.

This thesis will focus on the function to Conduct Deployment and Distribution, since this function typically consumes the largest amount of OE in a HADR operation. For the purpose of this thesis, this function shall be renamed as Conduct Resupply Operations for language consistency. Subsequently, this function can be further decomposed into three modes of resupply operations: (1) air-based logistics, (2) sea-based logistics, and (3) ground-based logistics. This thesis will only study the impact of ground-based logistics, however, for the following reasons. First, one of the most important tasks in HADR operations is the last mile distribution of relief supplies to affected victims, in particular to victims who may be displaced and isolated ; ground-based vehicles are most adept at performing this task, while sea-based assets are unable to achieve this objective. Second, air assets were not considered because they are considered less energy-efficient than ground-based vehicles, especially when they are tasked with distributing supplies to small, localized populations spread over large areas. Third, landing zones near isolated victims may be unavailable in the immediate situation after a disaster, and hence air assets are usually employed to deliver relief supplies from the sea base to land warehouses instead. Ruggedized military ground vehicles such as the Medium Tactical Vehicle Replacement (MTVR), however, are still able to traverse damaged and unpaved roads. For these reasons, ground-based logistics form the primary focus of this study.

In turn, ground-based logistics can be functionally decomposed into: (1) water production, (2) transport supplies, (3) provide storage, (4) perform maintenance, and (5) provide shelter (Alexander et al. 2011). See Figure 7. for the functional decomposition of ground-based logistics.

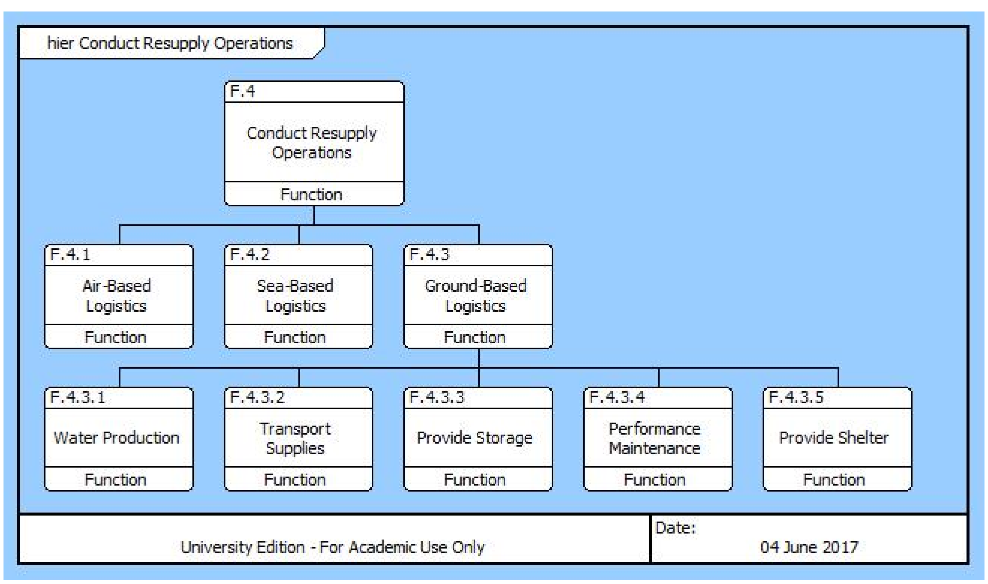

Figure 7. Functional Decomposition of Conduct Resupply Operations. Adapted from Alexander et al. .

As mentioned in Chapter I, this thesis studies whether or not the implementation of OE-focused assets and behaviors improves the operational reach of a resupply system for HADR operations. Hence, the refined functional decomposition shall only concentrate on the subset of ground-based logistics, and specifically the function of transporting supplies. This is because the transportation of supplies consumes the most OE and is most impacted by the increase/decrease in operational reach (Salem and Gallenson 2014). See Figure 8. for the refined functional decomposition of Conduct Resupply Operations.

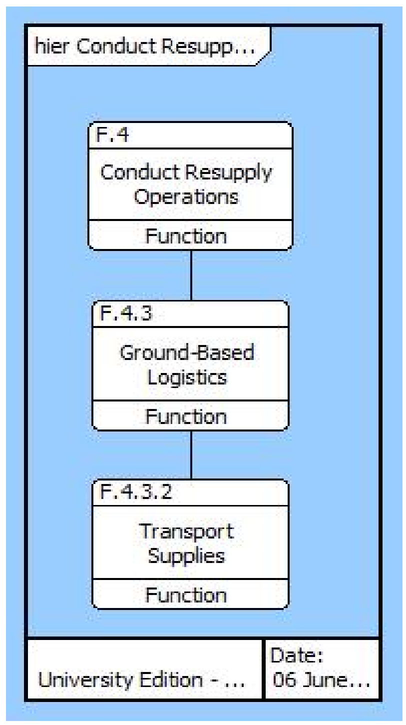

Figure 8. Refined Functional Decomposition of Conduct Resupply Operations.

C. BASELINE RESUPPLY CAPABILITIES

From the sample list of baseline equipment in Figure 5, the relevant equipment that the MEU can utilize for HADR resupply missions are listed in Table 2. Other unmanned logistics support vehicles such as the K-MAX helicopter were considered, but were ultimately not incorporated into this research, as they have not been fully equipped throughout all MEUs.

Table 2. Relevant Equipment for HADR Resupply Missions.

S/N	Equipment	Quantity
1	High Mobility Multipurpose Wheeled Vehicle (HMMWV)	105
2	Assault Amphibious Vehicles	15
3	Medium Tactical Vehicle Replacement (MTVR)	31
4	Excavator	1
5	MV-22B Osprey	22
6	CH-53E Super Stallion	4
7	UH-1N Huey	3
8	KC-130 Hercules	2
9	TRAM Forklift	2
10	5,000lbs Forklift	1
11	Extended Boom Forklift	1
12	D7 Bulldozer	1

This thesis does not consider unmanned logistics vehicles such as the K-MAX cargo resupply unmanned aerial system because it has not been deployed throughout all MEUs.

1. Analysis of Equipment Relevant for HADR Resupply Missions

In an analysis of the energy consumption of MEU equipment performed by Besser et al. using the Marine air-ground task force power and energy model (MPEM) (2013), it was revealed that the operation of air assets consumed the most amount of fuel per platform type, and left as a separate follow-on study. Hence, air assets are excluded from analysis in this thesis. The results of the MPEM analysis also revealed that it would be most beneficial to focus on reducing the logistical footprint, fuel consumption, and energy consumption of MTVRs (Besser et al. 2013). Indeed, given the MTVR's ability to traverse harsh terrain and transport food, water, and supplies, and that it is used by the USMC almost on a daily basis, it is one of the most suitable assets to be considered as the baseline resupply capability in HADR operations. Other ground-based assets such as armored assault vehicles, armored combat vehicles, and tanks were also considered but eliminated from further analysis due to their inability to transport and distribute large amounts of relief supplies, as well as low probability of their deployment in HADR resupply operations.

2. MTVR Capabilities

The MTVR is a seven-ton truck used by the USMC for ground maneuver and transportation operations. It has seven variants: (1) MK23 standard cargo truck, (2) MK25 standard cargo truck with winch, (3) MK27 extended cargo truck, (4) MK28 extended cargo truck with winch, (5) MK29 dump truck without winch, (6) MK30 dump truck with winch, and (7) MK36 wrecker. The selected variant to be used in this thesis is the MK23, as it is the most commonly used base model, and it contains all of the necessary capabilities to support a HADR resupply operation such as transporting bulk water and heavy equipment.

The MK23 (Figure 9.) is equipped with a cargo bed that can be configured to carry water tanks, bulk cargo, and refueling equipment. In terms of maneuverability, the MK23 is able to ford 60 inches of water and traverse over 24-inch vertical steps. This allows it to travel to disaster-affected areas where roads may be degraded/destroyed or obstructed by floods or building rubble. In terms of carrying capacity, the MK23 is able to carry up to 6.3 tons of payload while travelling on cross-country roads, which allows it to transport an ample amount of water and supplies. In sum, these capabilities are essential when operating in a HADR environment (Peters 2016).

Figure 9. MK23 MTVR in Standard Cargo Truck Configuration. Source: Jane's by IHS Markit (2014).

D. ENHANCED OPERATIONAL ENERGY-FOCUSED RESUPPLY STRATEGIES AND CAPABILITIES

In February 2011, the USMC published an Expeditionary Energy Strategy and Implementation Plan to “develop a plan to decrease the Marine Corps’ dependence on fossil fuels in a deployed environment” (USMC Expeditionary Energy Office 2011, 5). In particular, the plan states that the USMC aims to: “(1) embed expeditionary energy into USMC ethos, (2) lead and manage expeditionary energy, (3) increase the energy efficiency of weapon systems, platforms, vehicles, and equipment, and (4) meet operational demand with renewable energy.” The expeditionary energy goals and the expected efficiency targets that the USMC aims to progressively achieve are listed in Figure 10.

E^2 GOALS	Efficiency Gains		
	2015	2020	2025
Embed E^2 Into USMC Ethos	25%	40%	50%
Lead and Manage E^2			
Increase Energy Efficiency of Weapons Systems, Platforms, Vehicles, and Equipment			
Meet Operational Demand With Renewable Energy			

Figure 10. Expeditionary Energy Goals.
Source: USMC Expeditionary Energy Office (2011, 22).

Considering the aforementioned proposed goals by the USMC, this thesis studied several enhancements that aim to improve the usage of OE in a HADR mission to extend a MEU’s operational reach. Recommendations from this study revolve around the operation and capabilities of the MTVR as a good proxy for the enhancements to other ground-based vehicles.

1. Reducing Idling Time

Vehicle convoys are essential for HADR resupply operations. These convoys are planned operations to search for isolated disaster victims and distribute relief supplies to them. These operations also contribute to the most fuel wastage in terms of excessive vehicle idling, however. Currently, there are no pre-combat checks (PCCs) and tactics, techniques, and procedures (TTPs) for vehicle idling (Salem and Gallenson 2014, 31). Consequently, this has led to a mentality of "idling is just the cost of doing business" for Marines conducting convoy operations; without command emphasis and effective policies on reducing vehicle idling time, Marines are unable to translate increased energy efficiency to improved operational reach. Indeed, "observations captured during training exercises conducted at Marine Corps Air-Ground Combat Center (MCAGCC) in Twentynine Palms, CA found that excessive idling was prevalent throughout the training environment and observed on multiple occasions. Vehicles were left idling in excess of 20 minutes while Marines prepared for a tactical logistics convoy" (Peters 2016, 28–29). Failure to conduct proper PCCs and inspections also contributed to additional delays of more than 25 minutes while missing equipment was located . Instrumented vehicles were used during seven Integrated Training Exercises (ITXs) from 2013 to 2015, which allowed for vehicle data such as "vehicle run time, idle time, fuel consumption, and mileage" (Peters 2016, 29) to be captured and analyzed. The captured data is shown in Table 3. In particular, the idling time for MTVRs was 63.7%, which contributed to 26.7% of fuel wastage. The miles per gallon (MPG) without idling was 4.5 but decreased to 3.15 with idling, a 30% decrease (Department of the Navy 2010). In reality, some idling time cannot be totally prevented due to operational requirements or traffic conditions; nevertheless, the observations and data collected indicate there are significant OE gains to be reaped through reductions in vehicle idling time and fuel wastage.

Table 3. ITX Vehicle Data. Source: Department of the Navy .

Vehicle Type	Qty.	Engine hours	Idle hours	Idle Time (%)	Total Fuel (gal)	Idle Fuel (gal)	Idle Fuel (%)	Mileage	MPG with Idling	*MPG Without Idling
MTVR	736	49,301	31,414	63.7	123,322	32,983	26.7	388,315	3.15	4.5
LVSR	108	5,111	3,226	63.1	41,972	5,161	12.3	31,184	0.74	2.0
MRAP	45	2,857	2,219	77.7	4,522	1,553	34.4	11,993	2.65	--
MATV	26	1,523	1,158	76.0	3,875	810	20.9	6,562	1.69	--

2. Employing Trained Drivers

Numerous studies have been conducted regarding the effects of driving behavior on fuel efficiency, and it can be generally concluded that "aggressive driving behaviors such as fast acceleration and hard braking reduces fuel efficiency" (Peters 2016, 31). Indeed, a "fuel management study of medium and heavy ground-based vehicles including the MTVR" (Peters 2016, 31), performed by the Pennsylvania State Applied Research Laboratory, indicated that the "impact of erratic accelerator demand and excessive braking by the driver had detrimental effects on fuel economy" (Crow 2014, 2), and that "good driving habits offered a potential benefit of 30 percent in fuel economy improvements" (Crow 2014, 2). In addition, experiments conducted by the University of California, Davis also revealed that fuel economy differences from driving behaviors may vary up to nearly 30 percent between different drivers (Kurani et al. 2015). These two studies suggest that OE usage may be potentially reduced by the employment of trained drivers who are proficient at efficient driving techniques.

3. Employing Hybrid Technologies

Hybrid technologies have been widely adopted and implemented in the civilian automobile industry; indeed, most major carmakers today have at least one hybrid vehicle in their inventory list, (e.g., Toyota Prius, Hyundai Ioniq, Ford Fusion Hybrid, Chevrolet Volt). This has sparked interest in the military to explore hybrid technologies as a means to improve the energy efficiency of their ground vehicles as well. Firstly, hybrid technologies employ stop-start systems to stop the engine when a vehicle comes to a stop and automatically restart it to resume driving, regenerative braking, and large electric motors and batteries to reduce fuel consumption. Secondly, hybrid technologies may also serve as on-board generators to provide a source of auxiliary power to operators if needed. This eliminates the need to keep a vehicle idling when using its attached components, such as the heating, ventilation and air-conditioning system, improving fuel economy. Since hybrid systems range from hydraulic hybrid to diesel-electric, the DOD has invested funds to conduct research, development, test and evaluation (RDT&E) across a range of vehicles to determine which hybrid combination is the most feasible for military applications and yields the most fuel savings. For the MTVR, the Office of Naval Research (ONR) had engaged the original equipment manufacturer (OEM) Oshkosh Defense to produce a hybrid diesel-electric variant, dubbed the “ProPulse”—Oshkosh Defense claims that the ProPulse is able to improve fuel economy of the MTVR by up to 20% (Oshkosh Defence 2017).

4. Employing Follower Vehicle Technologies

The USMC Unmanned Ground Systems (UGS) Roadmap identifies that UGS are proving to be important for current combat operations, future contingencies, crisis response, and HADR scenarios (Besser et al. 2013). For a HADR resupply system, research indicates that autonomous and follower cargo vehicles may provide the required operational capabilities at a lower fuel consumption rate through efficiencies from automated driving, weight reduction, and reduced idling time. In particular, the Autonomous Mobility Appliqué System (AMAS) is an add-on robotics hardware kit that can be installed onto any MTVR to enable it to operate in a semi-autonomous/follower mode. The AMAS preliminary joint technology capability demonstration business case indicates that follower vehicles may achieve up to 7% in fuel savings due to optimized and fuel-efficient automated driving cycles (Besser et al. 2013).

E. OPERATIONAL SCENARIO

The operational scenario selected for constructing the simulation model is the support provided by the 31st MEU to the city of Hachinohe, Aomori prefecture as part of Operation TOMODACHI. Because ports were still operational after the disaster, Hachinohe and neighboring Miyako were selected as land bases for the HADR efforts along the affected northeastern coast of Japan (National Bureau of Asian Research 2014). The location of the ports at Hachinohe and Miyako is shown in Figure 11. Among other tasks, the 31st MEU delivered humanitarian aid supplies, including blankets and fresh water, to affected communities along the coast (Lubin 2011). The scenario starts after the 31st MEU’s sea-based HQ has unloaded relief supplies onto the land warehouses and LDCs. It concentrates on the first 72 hours of the ground resupply effort as the first 72 hours of a disaster relief effort is critical to the survival of isolated victims; the chance of survival beyond this time window decreases drastically without replenishment of food and water (Zeimpeikis et al. 2013, v).

Figure 11. Location of Operational Ports at Hachinohe and Miyako. Adapted from Google Maps.

F. THE MANA COMBAT SIMULATION TOOL

This thesis utilized a large-scale design of experiment (DOE) applied to an agent-based simulation. A typical simulation used by the Department of Defense (DOD) today involves hundreds to thousands of inputs, with multiple possible settings (levels) per input and many sources of uncertainty. As HADR resupply operations are complex and varied (Simoes-Marques and Nunes 2013), large-scale DOE methodology applied to simulation is hence suitable to capture and analyze such operations. Coupled with technological advances in computing power and state-of-the-art experimental designs, it is now possible to obtain deeper insights from large-scale DOE applied to simulations. Previously, DOE applied to simulations were constrained in scope due to limited computing resources. Additionally, haphazard exploration of simulations may miss important insights or worse, yield incorrect conclusions (Sanchez et al. 2012).

"MANA is an agent-based model developed at the Defence Technology Agency in New Zealand by the Operations Analysis group" (McIntosh 2009, 4). MANA is an example of an agent-based simulation, which means that it may be able to capture unanticipated emergent interactions between agents, which may give rise to a wider range of potential outcomes. More specifically, MANA is "an agent-based distillation model" (Anderson 2013, 1), which means that it intends to capture only as much physical detail as necessary, but yet is still capable of producing required data for more complex analysis. Lastly, MANA is also known as a "complex adaptive system because of the way that the agents react with each other in the simulated environment; the 'global' behavior of a system 'emerges' as a result of the many localized interactions between the agents" (McIntosh et al. 2007, 5). Indeed, such is the usefulness and efficiency of MANA that there have been a number of theses completed at the Naval Postgraduate School (NPS) that have utilized MANA as their simulation tool, such as Wolf (2003), Hinkson (2010), and Cheang (2016).

Continuous development and upgrades of the MANA model have been ongoing since the first version was released in 2000. MANA-Vector (MANA-V) version 5.01.09 was used in this thesis. In this version, a vector-based approach is implemented for agent-based movement, as compared to a grid-based scheme used in previous versions. This allows all distances, sensor and weapon ranges, and agent speeds to be defined in terms of *Système Internationale* units. This eliminates the need to convert real-world distances to number of grid squares, and provides greater flexibility in developing new model features (McIntosh 2009).

G. MANA SIMULATION MODEL

This section describes the implementation of the operational scenario as described in Section E in MANA. Firstly, it describes the goals and concept of the model. Secondly, it presents the assumptions used in the construction of the model. Lastly, it describes the agents used in the model, as well as certain workarounds required to simulate the act of resupply in MANA, since MANA has no such predefined function.

1. Goal of Simulation Model

Typical HADR operations involve three broad phases: (1) emergency response, (2) relief provision, and (3) restoration to normalcy (Multinational Planning Augmentation Team 2010). This thesis will only study the land-based resupply operations conducted in Phase 2. Specifically, the scenario starts after a MEU sea-based HQ unloads relief supplies onto land warehouses. The modeling effort will help to derive insights on the effectiveness of OE-focused assets in supporting the logistical capability and throughput of the land distribution of relief supplies.

2. Conceptual Model

The simulation represents a distribution model as shown in Figure 12. There are two types of storage entities for relief supplies: (1) LDCs (the land warehouses) and (2) dynamic distribution teams (DDTs). The LDCs act as a stockpile for relief supplies, while the DDTs search for and distribute relief supplies to the isolated victims. The storage entities have different storage capacities and are used to store two categories of HADR supplies most essential for immediate survival: (1) food/supplies and (2) water. For the purpose of simulation in MANA, these supplies will be amalgamated into one resource known as "ammunition," and each supply entity will begin at its fully loaded capacity at the start of the simulation. As the simulation runs, the DDTs will consume fuel as they travel around the disaster area searching for isolated victims. As the disaster area is often damaged, isolated victims may be difficult to locate. This is captured in MANA by assigning an initial concealment value to the victims. The concealment value serves as a "stealth" factor within the simulation; the higher the concealment of an agent, the more difficult it is to detect and classify it with a sensor. When DDTs are able to detect, classify, and thus locate, a victim, the DDTs will then be able to "shoot" the victim with a special non-lethal "weapon" whose single shot of ammunition represents the delivery of relief supplies to the isolated victim. When a resupplied victim encounters a yet-to-be resupplied victim within his user-defined local "neighborhood," he will engage in a simulation interaction that is meant to capture that he informs the latter and the DDTs of the presence of other victims. This interaction causes the concealment value of the yet-to-be resupplied victim to go to 0%, as he tries to make himself more visible to the DDTs in order to be resupplied. When the DDTs run out of supplies (ammunition) or fuel, they will return to the land warehouses for resupply using a "pull" concept. The DDTs will always move out from the LDCs at full ammunition and fuel levels. If a DDT returns to a land warehouse but finds the warehouse in the process of resupplying other DDTs, it must wait its turn to be resupplied before it can receive a full supply of fuel and ammunition and consequently be able to move out for another mission.

Figure 12. HADR Resupply Model.

3. Map Information

A map image obtained from Google Maps of Hachinohe and the surrounding area (including the Aomori and Iwate prefectures) is used as the background map for this thesis (Figure 13.). The dimension of the map is defined to be 60 miles by 100 miles (Figure 14.). No relief or elevation information was used in this model as this level of detail was not considered necessary for this study; the DDTs must be able to traverse degraded roads, building debris, and forested areas to reach the affected victims.

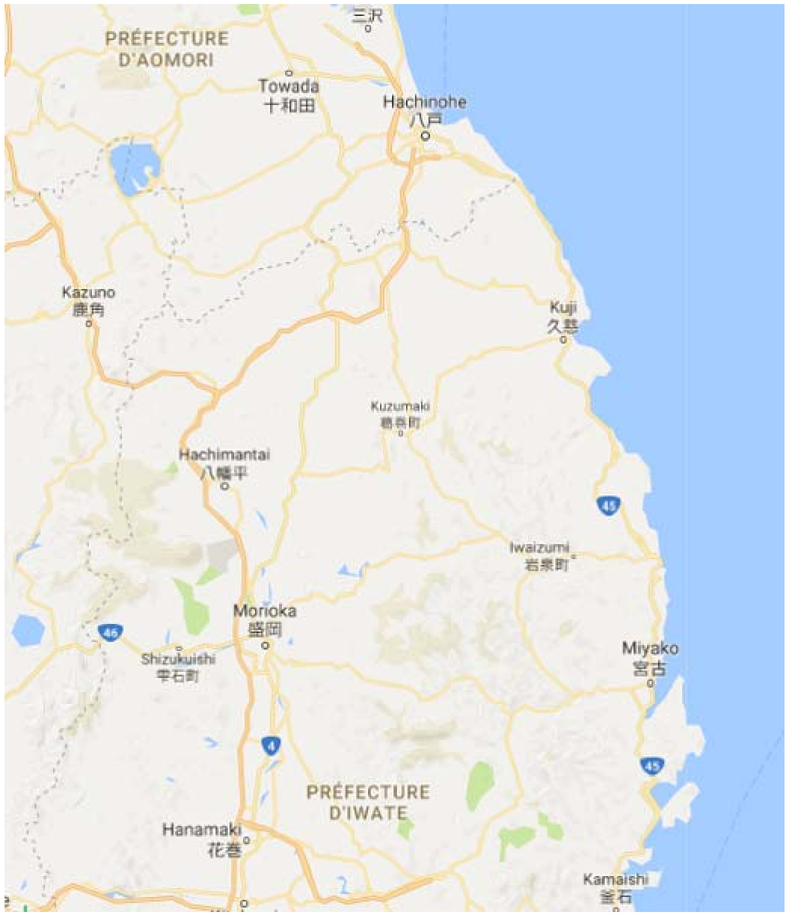

Figure 13. Map of Hachinohe and the Surrounding Areas Used in MANA.
Source: Google Maps.

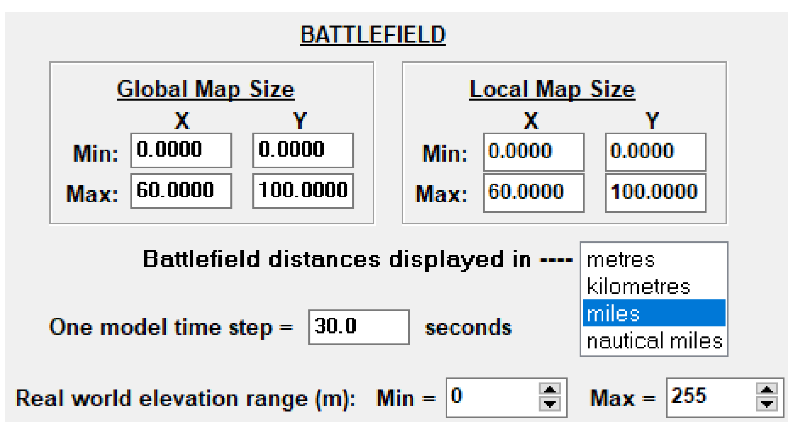

Figure 14. Map Size Used in MANA.

A terrain map (Figure 15.) is used by MANA to influence the movement of agents in the simulation model. Essentially, a bitmap image is used to represent different types of terrain using a variety of colors. Each color represents a set of values for terrain characteristics such as "Going," "Cover," and "Conceal." The values range from 0.00 to 1.00. A value of 1.00 for "Going" means that movement is unobstructed, while a value of 0.00 for "Going" means that the piece of terrain is unpassable. The characteristics for "Cover" and "Conceal" are not used in this thesis. Among the range of terrain types available, this thesis only uses three types of terrain: dirt, road, and water. Dirt is represented by the color brown, and represents building rubble and degraded roads. Roads are represented by the color yellow, and represent trafficable roads in the map. Water is represented by the color blue, and is not trafficable for MTVRs.

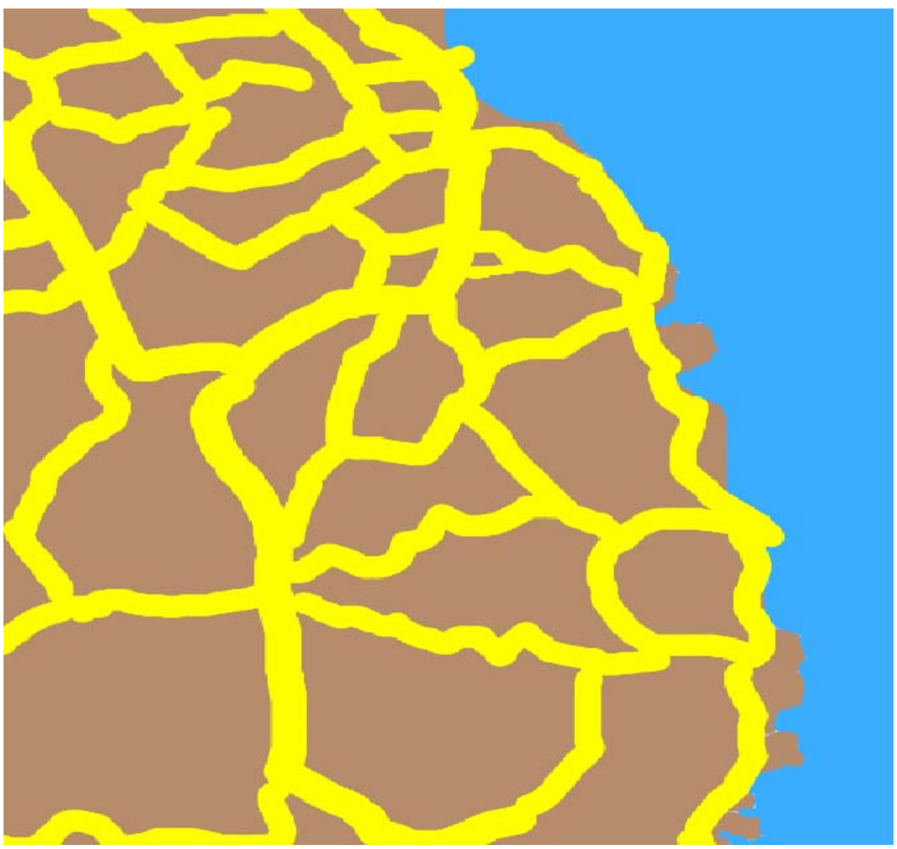

Figure 15. Simulation Terrain Map.

The simulation terrain properties are shown in Table 4. The pertinent values for this thesis are highlighted in red boxes.

Table 4. Simulation Terrain Properties.

	Going	Cover	Conceal	Red	Green	Blue
BilliardTable	1.00	0.00	0.00	0	0	0
Wall	0.01	1.00	1.00	192	192	192
Hilltop	0.90	0.10	0.95	64	64	64
Road	1.00	0.00	0.00	255	255	0
LightBush	0.75	0.10	0.30	10	255	10
DenseBush	0.20	0.30	0.90	40	180	40
Water	0.00	0.00	0.00	58	173	255
Dirt	0.70	0.00	0.00	183	140	108

4. Data Sources and Assumptions

Effort was made to use credible data sources and reasonable assumptions to create a representative model capable of providing useful insights. One limitation to the study is the author's non-access to U.S. classified data about the actual operations and after-action reports, however. Hence, most data sources are from past master's theses from NPS and unclassified information about similar operations or related subjects. The E2O also provided data and feedback through email consultation, monthly updates, and quarterly in-progress briefings. Key assumptions used in the MANA model are as follows:

1. The 31st MEU has completed the sea-to-ground transfer of relief supplies to the LDCs.

2. LDCs contain sufficient supplies to resupply all isolated victims; no resupply to the LDCs is required in the simulation. For the simulation, five LDCs are utilized. The locations of the LDCs are shown in Figure 16, as blue "plus" signs surrounded by yellow circles.

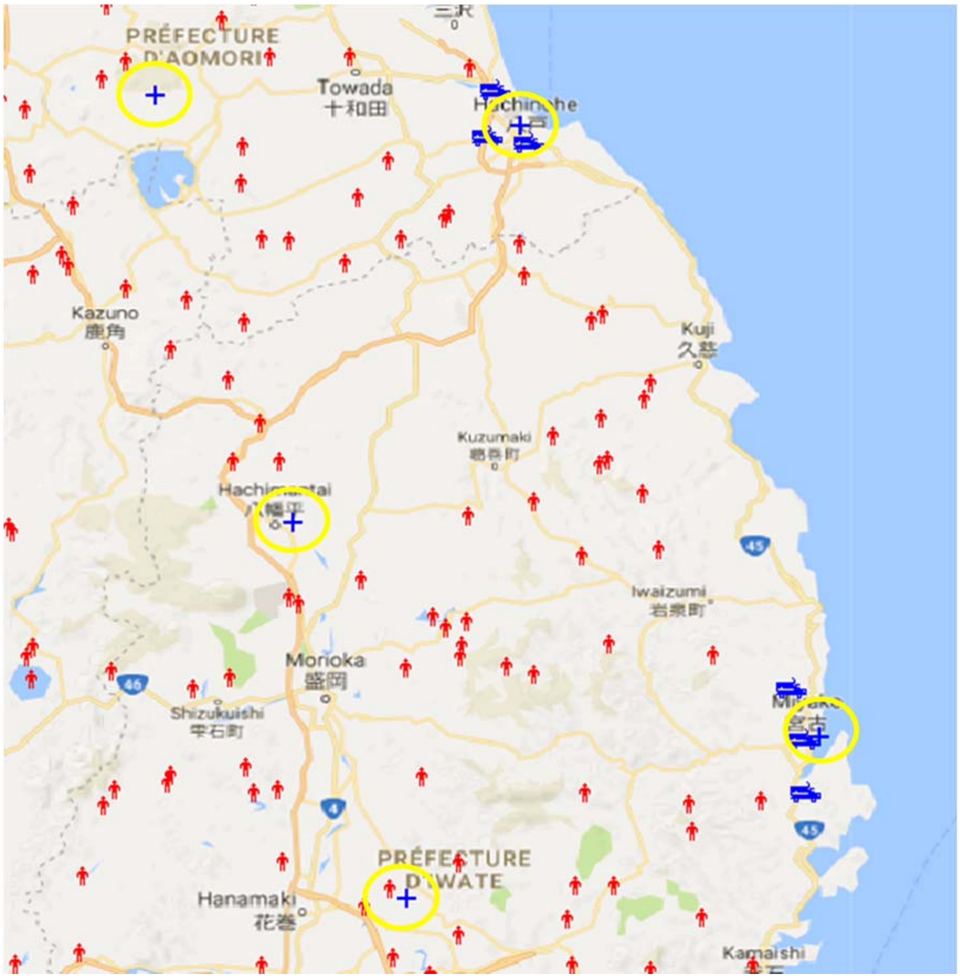

Figure 16. Location of LDCs. Adapted from Google Maps.

3. The relief supplies at Hachinohe are used to aid survivors in neighboring Aomori and Iwate prefectures. Literature study indicates that there were about 4,000 people missing (Table 5). It is also assumed that they congregate in groups of 40 each, resulting in a total of 100 victim agents in the simulation. It is further assumed that the missing people are randomly dispersed across three areas in the map (Figure 17.); victims are distributed proportional to the size of their homebox. A homebox is a term used in MANA to refer to the default location of an agent in the scenario map. Based on their relative homebox sizes, H0 contains 34% of victim agents, H1 contains 6% of victim agents, and H2 contains 60% of victim agents.

Table 5. Population Affected by Tsunami. Adapted from Vervaeck and Daniell (2011).

Prefecture	Prefecture Name 2	Daytime Population	Deaths	Missing	Total Injured	Total People in Shelters (regardless of Prefecture)
Hokkaido	Hokkaido	5,507,456	1		3	1021
Aomori	Aomori-ken	1,373,164	3	1	61	815
Iwate	Iwate-ken	1,330,530	4,047	3,822	165	44515
Miyagi	Miyagi-ken	2,347,975	8,505	7,884	3436	43588
Akita	Akita-ken	1,085,878			12	539
Yamagata	Yamagata-ken	1,168,789	2		29	1438
Fukushima	Fukushima-ken	2,028,752	1412	2,044	227	26273
Tokyo	Tokyo-to	13,161,751	7		90	942
Ibaraki	Ibaraki-ken	2,968,865	23	1	693	677
Tochigi	Tochigi-ken	2,007,014	4		135	901
Gunma	Gumma-ken	2,008,170	1		35	2928
Saitama	Saitama-ken	7,194,957			42	3581
Chiba	Chiba-ken	6,217,119	18	2	224	1257
Kanagawa	Kanagawa-ken	9,049,500	4		139	695
Niigata	Niigata-ken	2,374,922			3	4695
Yamanashi	Yamanashi-ken	862,772			2	840
Shizuoka	Shizuoka-ken	3,765,044			4	755
Gifu	Gifu-ken	2,081,147				
Mie	Mie-ken	1,854,742			1	
Nagano	Nagano-ken	2,152,736				909
Miyakazi	Miyazaki-ken	1,135,120				
Tokushima	Tokushima-ken	785,873				
Kochi	Kochi-ken	764,596			1	
Total		73,226,872	14,027	13,754	5,302	136,369

Figure 17. Distribution of Isolated Victims. Adapted from Google Maps.

4. At the beginning of each simulation run, it is assumed that DDTs all start out either at the port of Hachinohe or the port of Miyako. It is planned for DDTs from the port of Hachinohe to supply isolated victims in homeboxes H0 and H1, while DDTs from the port of Miyako are used to supply isolated victims in homebox H2. Consequently, the number of DDT convoys are distributed proportionally according to the number of victims that the DDTs are intended to supply (i.e., approximately 40% of total DDT convoys will depart from Hachinohe, while approximately 60% of total DDT convoys will depart from Miyako). In operational plans where there are fewer DDT convoys than homeboxes, some homeboxes may not be occupied and there will be some areas that may not be able to be covered during the simulation runs due to time or vehicle constraints. The locations of the DDT homeboxes are shown in the Appendix. The number of DDT agents in each homebox is listed in Table 6.

Table 6. Number of DDT Agents in Each DDT Homebox.

Operational Plan	Homebox H0	Homebox H1	Homebox H2	Homebox H3	Homebox H4	Homebox H5
1	1	1	0	1	1	1
2	1	0	0	1	0	0
3	0	1	1	1	1	1
4	0	1	0	1	0	1
5	1	2	1	2	2	2
6	1	0	1	1	1	1
7	1	1	0	0	1	1
8	1	1	0	1	1	1
9	2	2	2	3	3	3
10	2	1	1	2	2	2
11	1	1	1	1	1	1
12	0	1	1	1	1	1

5. To speed up calculations, this simulation utilizes 30 seconds per time step. The scenario runs for 72 hours as the first 72 hours of a disaster relief effort is critical to the survival of isolated victims (Zeimpeikis et al. 2013), which equates to 8,640 time steps.

6. It is assumed that the isolated victims will be provided with three days' supply (DOS) as an interim solution. For comparison, planning parameters indicate that Marines carry with them one DOS when conducting dismounted operations, and are also supported by one DOS by the combat train. Eventually, the goal is to enable the disaster victims to recuperate and travel to shelters set up by NGOs for further treatment and centralized distribution of supplies.

7. Literature study indicates that a total of 3.1 pounds (1.5kg) of aid, per person, per day, is required for daily replenishment. (Alexander et al. 2011). In addition, USAID stipulates that 15 liters of water, per person, per day, is required to meet minimum survival standards. In total, it is assumed that the amalgamated relief supply quantity is 16.5kg per person

per day; 49.5kg (≈ 50kg) of relief supplies are required per person for 3 days.

8. It is assumed that the DDTs deliver potable water to the isolated victims. Water foraging technologies such as water purification tablets and LifeStraws are out of the scope of this thesis.

9. It is assumed that the roads are significantly damaged, and hence MTVRs are required for the DDTs to deliver supplies to isolated victims.

10. USMC standard operating procedure (SOP) for convoy operations states that convoy speeds should be decreased to maintain convoy integrity for longer convoys (USMC 2017b). In general, realistic parameters for a convoy travelling on country roads for operations other than war are 15 to 40 km/h (10 to 30 MPH) (Schrepf 1999). Taking 10 MPH as a lower bound and 30 MPH as an upper bound, and assuming a linear correlation between convoy length and convoy speed (GlobalSecurity 2017), the DDT convoy lengths and their respective convoy speeds used in this thesis are listed in Table 7.

Table 7. Convoy Length and Convoy Speed.

Convoy Length	Convoy Speed (MPH)
2	30
3	25
4	20
5	15
6	10

11. Although vehicle speed generally has an inverse relationship with fuel efficiency, it is assumed that the speed of the DDT convoys does not affect their fuel consumption. This is because the speeds of the DDT convoys in this thesis only range from 10 to 30 MPH (Table 7). Fuel efficiency usually decreases only at speeds above 50 MPH (U.S. Department of Energy 2017).

12. It is assumed that the default sensor range of the DDT convoys is 3,000m as human-scale objects are resolvable as extended objects from a distance

of just under 3,000m (Wolchover 2012). Further, it is also assumed that the effectiveness of the DDTs in locating isolated victims is inversely related to their convoy speed. This is because longer and slower convoys are able to spend more time scanning the environment, and they have more manpower to scan for isolated victims. Assuming that the sensor range factor decreases by 5% for every five MPH increase in convoy speed, the DDT convoy speeds and their respective sensor range factors used in this thesis are listed in Table 8.

Table 8. Convoy Speed and Sensor Range Factor.

Convoy Speed (MPH)	Sensor Range Factor
30	0.80
25	0.85
20	0.90
15	0.95
10	1.00

13. Out of the total carrying capacity of 6.3 tons of the MTVR, it is assumed that the space allocated for relief supplies is 6 tons due to the need to transport troops and other equipment for HADR (e.g., medical relief equipment, and search and rescue equipment). This translates to each MTVR being able to carry two shots of "ammunition" representing relief supplies. One shot of "ammunition" is able to resupply one victim cluster of 40 victims.

14. It is assumed that the default fuel efficiency of the MTVR is a constant 4.5 MPG (Table 3). In reality, the fuel efficiency is a function of driving behavior, proportion of time idling, terrain, and how heavily the MTVR is loaded.

15. It is assumed MTVRs move along pre-planned routes as decided upon by the MEU commander. An example of a pre-planned route in MANA is shown in Figure 18. Images of all six pre-planned routes used in this thesis are shown in the Appendix.

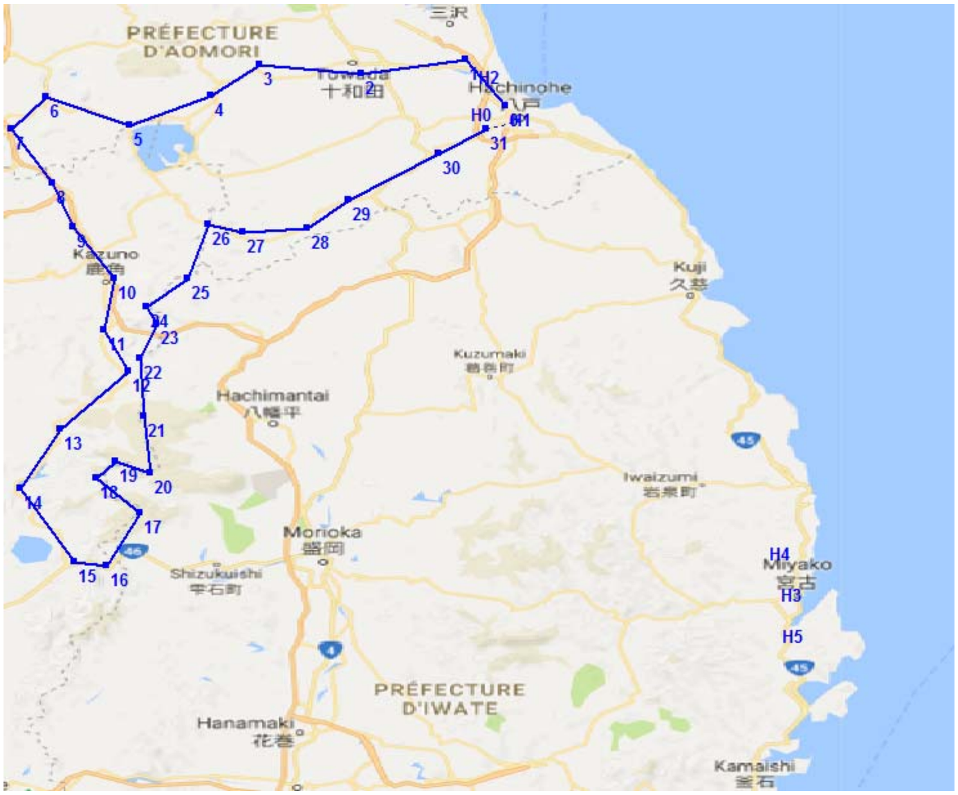

Figure 18. Example of a Pre-Planned Route in MANA.
Adapted from Google Maps.

16. Akin to search and rescue missions, it is assumed that the MTVRs do not have any prior knowledge of the location of isolated victims.

17. It is assumed that DDTs will begin to return to the LDC for refueling once they have consumed 70% of their available fuel (i.e., 30% of the fuel capacity is sufficient for the DDTs to travel back to the nearest LDC for refueling).

18. It is assumed that DDTs do not consume fuel when they are being resupplied or refueled.

19. It is assumed that the DDTs will return to the closest LDCs for refueling or reloading at the point when they run low on fuel or out of supplies. It is further assumed that they will not resupply any disaster victims when they are traveling back to refuel or reload supplies.

20. It is assumed that the resupply operations are conducted non-stop during the 72 hours due to the urgency of the mission.

5. LDCs

The LDCs are used to store relief supplies; with reference to Section B of this chapter, they perform the function of "Provide Storage." They may be sited at the location of existing warehouses, or in improvised areas such as parks or open spaces closer to the affected victims. The DDTs will refuel and stock up at the LDCs when they run out of either gas or relief supplies. To model the refueling or resupply behavior, MANA's state, sensor, and weapon properties were used. At the beginning of the scenario, all the DDTs are fully loaded and are invisible to the LDCs. When a DDT only has 30% of fuel remaining, or is out of relief supplies, it undergoes a state change and become visible to the LDCs. This is called the "fuel out" state in MANA, but we refer to it as the "fuel low" state throughout this thesis. When a visible DDT is within range of an LDC, the LDC will "shoot" it with a special (non-lethal) weapon. This weapon does not kill or injure the DDT; the weapon merely triggers the "shot at" state change in the DDT. In this state, the DDT enters a delay (0.5 hours) that captures the time taken for it to receive its restock (reload of ammunition). This duration does not depend on the remaining supplies that it may still have on board; the resupply duration is assumed to be a constant 0.5 hours. Additionally, the LDC has a short-range refueling capability that causes the DDT it is servicing to receive its full tank of fuel. Upon the expiration of the time delay, the DDT resumes its default state in which it returns to its mission of locating victims and supplying them.

6. DDTs

The DDTs perform the function of "Transport Supplies" as described in Section B of this chapter. In this thesis, a DDT agent represents a vehicle convoy that searches for and distributes relief supplies to isolated victims. The DDTs use MTVRs to deliver supplies to these victims, and they travel in convoys varying from two to six MTVRs. In Section G.4.8, it was mentioned that the carrying capacity of each MTVR for relief supplies is six tons. As such, a DDT agent may carry 12 tons to 36 tons of relief supplies when fully loaded, depending on the number of vehicles in a convoy. In all, there are 30 MTVRs available for the MEU to deploy to conduct resupply operations. As the simulation runs, the DDTs consume fuel as they travel around the disaster area searching for isolated victims. The speed of the DDT depends on the convoy length; the longer the convoy length, the slower the speed to maintain convoy integrity (USMC 2017a). When a victim cluster falls within the sensor range of the DDTs and is seen by them, the DDTs will deviate from their predefined search waypoints and "shoot" the victim cluster with ammunition, simulating the provision of relief supplies to isolated victims. The DDTs can only resupply one victim cluster at a time. While they are supplying relief victims, the DDTs remain in place for 0.5 hours. The default state of the DDT represents when it has fuel or relief supplies and is on mission. In this state, it is represented in the simulation animation screen by a blue truck icon. Its icon turns purple when it has 30% of fuel remaining (triggering a state change) and turns red when it is out of relief supplies. In the yellow or red state, its behavior will be to move to the nearest LDC to be refueled and restocked. In the simulation, it moves in a straight line, perhaps through cross-country terrain, to the closest LDC, emphasizing the need to be refueled or restocked. After it is refueled or restocked, the DDT will return to its previous location to continue to search for victims in the vicinity.

7. Isolated Victims

Isolated victims may be caught in landlocked areas in the aftermath of a disaster, and thus be unable to collect supplies from local distribution centers. The mission of the DDTs is to search for these isolated victims in order to provide them with relief supplies. In the model, there are 100 clusters of isolated victims randomly distributed across three areas in the map. Each cluster represents 40 victims. The victims are unable to move to shelters due to a lack of supplies and inaccessible roads. As each victim requires 50kg of supplies per three days, each cluster will require 2,000kg (2 metric tons) of supplies. In their default state, the isolated victims are red in color and have a concealment value of 50% to simulate the DDTs searching for the victims. When they are supplied by a DDT, they enter the "shot at" state, in which they turn green in color and become invisible to the DDTs so that the DDTs do not waste time re-encountering the same victim. As mentioned previously, isolated victims may also see other isolated victims within a user-defined local neighborhood. When a resupplied victim encounters a yet-to-be resupplied victim, the simulated interaction captures that the resupplied victim will be able to inform both the nearby unsupplied victims and the DDTs about the presence of the other, which causes the concealment value of the yet-to-be resupplied victim to drop to 0% as that victim tries to become more visible to the DDTs in order to be resupplied. When the concealment value drops to 0%, the color of the isolated victim changes from red to yellow.

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IV. MODEL EXPLORATION

A. INTRODUCTION

The MOEs directly address the research questions stated in Chapter I, Section F; one or more measures of performance (MOPs) may be related to the achievement of a particular MOE (Hernandez 2016). As such, each MOP is a quantitative assessment of the performance of a particular capability toward meeting stakeholder needs. A robust DOE was used to vary input factors used in numerous simulation runs to generate data. Input factors explored in this study include OE-focused assets and driver behavior. The JMP Pro 12 statistical discovery software from the SAS Institute Inc. was used to derive important insights regarding the impact of input factors on MOEs, MOPs, and the interactions between those factors.

B. MOES AND MOPS

MOEs are measures or metrics designed to correspond to the achievement of mission objectives and achievement of desired results. Good MOEs are relevant, linked to the strategic end state, precisely defined, observable, and quantifiable . With respect to the research questions listed in Chapter I, Section F, the associated MOEs are defined as follows:

1. Throughput of relief supplies to isolated victims
2. Timeliness in delivering relief supplies to isolated victims
3. Fuel efficiency of each capability instantiation

MOPs are measures of a system's performance expressed as a distinctly quantifiable performance feature and are logically linked to the performance or objective that is to be realized (Hernandez 2016). Hence, MOPs must be relevant to the MOEs. In addition, the data required for each MOP in this study must be obtained through the MANA simulation model. Table 9 lists the MOEs, MOPs, and data requirements used in this thesis. The objective of each data requirement is also listed as more is better (MIB), or less is better (LIB).

Table 9. MOEs, MOPs, and Data Requirements.

MOE	MOPs	Data Requirements	MOE Objective
1. Throughput of relief supplies to isolated victims	1. Number of victim clusters resupplied	a. Total number of victim clusters resupplied at the end of three days	MIB
	2. Probability of resupplying victim clusters	b. Number of cases where 50% of victim clusters were resupplied	
		c. Number of cases where 75% of victim clusters were resupplied	
		d. Number of cases where 100% of victim clusters were resupplied	
2. Timeliness in delivering relief supplies to isolated victims	3. Lower bound on the time taken to resupply victim clusters	e. Time taken to resupply 50% of victim clusters	LIB
		f. Time taken to resupply 75% of victim clusters	
		g. Time taken to resupply 100% of victim clusters	
3. Fuel efficiency of each capability instantiation	4. Fuel consumed	a. Total number of victim clusters resupplied at the end of three days	MIB
	5. Fuel consumed per victim cluster resupplied	a. Total number of victim clusters resupplied at the end of three days	
	6. Lower bound on the fuel consumed to resupply victim clusters	e. Time taken to resupply 50% of victim clusters	
		f. Time taken to resupply 75% of victim clusters	
		g. Time taken to resupply 100% of victim clusters	

MOPs 1 and 2 together define MOE 1. MOP 1 measures the total number of victim clusters who were resupplied at the end of three days. This is a direct measurement of the effectiveness of each capability instantiation toward the throughput of relief supplies to disaster areas; the more victim clusters resupplied the better. MOP 2 measures the probability of each capability instantiation in resupplying: (1) 50%, (2) 75%, and (3) 100% of victim clusters. In addition to the number of victim clusters resupplied, it is also important to measure the likelihood that each capability instantiation can resupply a certain percentage of victim clusters. The higher the probability of resupplying a certain percentage of victim cluster, the better.

MOP 3 defines MOE 2. It measures the lower bound time to resupply: (1) 50%, (2) 75%, and (3) 100% of victim clusters. HADR resupply operations are time-critical. Ensuring victim survivability entails measuring the timeliness in resupplying the victim clusters, and thus, a relevant MOE as well. The less time taken to resupply a certain percentage of victim clusters, the better.

MOPs 4, 5, and 6 define MOE 3. MOP 4 is a proxy measurement of the quantity of fuel utilized by the DDTs in carrying out resupply operations. As defined by Keeny and Raiffa (1993, 55), "a proxy attribute is one that reflects the degree to which an associated objective is met but does not directly measure an objective." As the DDTs are refueled as well when they return to the LDCs in an "ammunition out" state, it is difficult to measure the exact quantity of fuel used because MANA is unable to account for the quantity of fuel that the DDTs receive in these instances. However, MANA is able to be configured to provide requirement (a), the total number of victim clusters resupplied at the end of three days. The fuel consumed can then be calculated by taking the product of the amount of time that the DDTs consume fuel with its fuel consumption rate in gallons per hour (GPH). The amount of time that the DDTs consume fuel is obtained by subtracting the amount of time that they are stationary from the amount of time that are moving. The amount of time that the DDTs are stationary is calculated by taking the product of the number of victim clusters resupplied, amount of time taken to resupply each victim cluster (0.5 hours), and whether or not it consumed fuel while resupplying victim clusters (binary variable "1" or "0"). The maximum amount of time that the DDTs are moving is calculated by taking the product of the number of MTVRs utilized and total operational time (72 hours). In mathematical notation,

$$FuelConsumed=[(No.DDTsUtilized\times 72)-(No.VictimsResupplied\times 0.5\times ReduceIdleTime)]\times GPH$$

Hence, the total number of victim clusters resupplied at the end of three days can be used to calculate a proxy measurement for the quantity of fuel utilized; the less fuel consumed, the better. However, less fuel consumed may not necessarily indicate success for the resupply operation; it is more meaningful to measure the fuel utilized per victim cluster resupply in order to measure fuel efficiency. This is done in MOP 5, which is a proxy measurement for the amount of fuel utilized per victim cluster resupplied. The less fuel consumed per victim cluster resupplied, the better the fuel efficiency. Lastly, MOP 6 measures the lower bound fuel utilized to resupply: (1) 50%, (2) 75%, and (3) 100% of victim clusters; the less fuel consumed, the better the fuel efficiency.

C. INPUT FACTORS

Experiment design factors consist of simulation input parameters of interest, or functions of simulation inputs. The set of design factors represents the set of inputs that are varied via the experimental design. Generally, the input factors can be grouped into two categories: (1) controllable and (2) uncontrollable.

Controllable factors, or decision factors, are factors that can be changed or influenced by decision makers. On the other hand, uncontrollable factors, or noise factors, are those over which decision makers have little or no control (Kleijnen et al. 2005). Both decision and noise factors are included in the simulation design because both have an impact on output statistics, including measures of variability, which can be used as an indicator of risk. The decision and noise factors are listed in Table 10. Factors highlighted in blue are the decision factors, and factors highlighted in red are the noise factors.

Table 10. Decision and Noise Factors.

Factor	Factor Type	Min	Max	Description
Operational Plan	Categorical / Discrete	1	12	The number of MTVRs, and convoy length of each DDT, used by the MEU to conduct HADR resupply operations. The different combinations affect the convoy speed and the amount of relief supplies that a DDT convoy is able to carry.
Reduce Idle Time	Categorical / Discrete (Binary)	0	1	A binary variable to determine if the MEU adopts policies that aim to reduce idling time. If adopted, the MTVRs do not consume fuel when they are unloading relief supplies to victims.
Fuel Efficiency	Continuous	3.15	5.778	The fuel efficiency of MTVRs is affected by employing: (1) trained drivers, (2) hybrid technologies, and (3) follower vehicle technologies.
Communication Devices	Continuous	3,000	10,000	The employment of communication devices to allow DDT convoys to see beyond the line of sight in the search for isolated victims.
Concealment	Continuous	0.25	0.75	The detectability of isolated victims.
Trafficability	Continuous	0.5	0.75	The trafficability of roads in the area of operations.

1. Decision Factors

a. Operational Plan

In Chapter III, Section G.6, it was stated that there are 30 MTVRs available for the MEU to deploy to conduct resupply operations. The MEU commander may choose to deploy all or a partial number of MTVRs to conduct resupply operations. In this thesis, the MEU commander has a choice of deploying 10, 15, 20, 25, or 30 MTVRs for resupply operations. In addition, it was mentioned that the DDTs travel in convoys varying from two to six MTVRs. As the carrying capacity of each MTVR for relief supplies is six tons, the amount that a fully loaded DDT may carry varies from 12 tons to 36 tons, depending on the convoy length that the MEU commander chooses to use. The length of convoy impacts the: (1) speed of convoy and (2) amount of relief supplies carried by each DDT. The longer the convoy, the slower the convoy speed; this is USMC SOP to maintain convoy integrity (USMC 2017b). More relief supplies can be carried and hence distributed by longer convoys, however. In addition, longer convoys are also more effective in locating isolated victims, as: (1) they are able to spend more time scanning the environment and (2) they have more manpower to scan for isolated victims. This thesis studies 12 possible operational plans generated by the combination of the two decision factors. The operational plans and their respective data are listed in Table 11. It is to be noted that due to vehicle constraints, eight operational plans (1, 2, 3, 4, 6, 7, 8, 12) will not cover all pre-planned routes, while four operational plans (5, 9, 10, 11) will cover all pre-planned routes.

Table 11. Operational Plan, Number of MTVRs Used, and Length of DDT Convoy.

Operational Plan	Number of MTVRs Used	Length of DDT Convoy	Number of DDT Agents	Convoy Speed (MPH)	Relief Supplies per DDT (Ton)	Sensor Range Factor
1	10	2	5	30	12	0.80
2	10	5	2	15	30	0.95
3	15	3	5	25	18	0.85
4	15	5	3	15	30	0.95
5	20	2	10	30	12	0.80
6	20	4	5	20	24	0.90
7	20	5	4	15	30	0.95
8	25	5	5	15	30	0.95
9	30	2	15	30	12	0.80
10	30	3	10	25	18	0.85
11	30	5	6	15	30	0.95
12	30	6	5	10	36	1.00

b. Reduce Idle Time

Chapter III, Section D.1 explored the adverse impact of idling time on fuel efficiency. Two instantiations were generated to explore this behavior. If the drivers do not reduce idling time, the DDTs continue to consume fuel when they are resupplying affected victims. If the drivers reduce idling time, the DDTs will not consume fuel when they are resupplying affected victims. The "My Fuel Usage Rate" parameter is utilized to simulate whether the DDTs continue to consume fuel or not in the resupply "taken shot" state. The two instantiations and their data are listed in Table 12.

Table 12. Instantiations for Reduce Idle Time.

Instantiation	Consume Fuel During Resupply
0	Yes
1	No

c. Fuel Efficiency

Chapter III, Section G.4 states that the default fuel efficiency of the MTVR is 4.5 MPG. In this thesis, the employment of (1) trained drivers, (2) hybrid technologies, and (3) follower vehicle technologies will cause this default value, either adversely or positively, to range from 3.15 MPG to 5.778 MPG. The final fuel efficiency value is obtained by taking the product of the MPG multipliers for employing trained drivers, hybrid technologies and follower vehicle technologies, with the default fuel efficiency. In mathematical notation, the final fuel efficiency can be calculated from

$$FinalFuelEfficiency = \prod_{AllMPGMultipliers} \times DefaultFuelEfficiency$$

The lower bound is derived from the employment of 0% trained drivers, 0% hybrid technologies, and 0% follower vehicle technologies, and this results in a final MPG of $0.7 \times 1.0 \times 1.0 \times 4.5 = 3.15$ MPG. Similarly, the upper bound is derived from the employment of 100% trained drivers, 100% hybrid technologies, and 100% follower vehicle technologies, and this results in a final MPG of $1.0 \times 1.2 \times 1.07 \times 4.5 = 5.778$ MPG. Descriptions of the factors affecting fuel efficiency follow.

(1) Employing Trained Drivers

Chapter III, Section D.2 explored the benefits of efficient driving techniques on fuel efficiency; fuel economy differences from driving behaviors may vary by up to nearly 30 percent between different drivers (Kurani et al. 2015). In a MEU, trained or incidental operators are allowed to operate ground vehicles. A trained driver is one who has attended specialized motor training courses and is identified with the 353X motor transport driver designation; an "incidental operator is qualified to drive, but driving may not be his specialty in the USMC" (Peters 2016, 39). Literature survey indicates that "incidental vehicle operators are less likely to comply with best driving practices and are more prone to 'gunning the vehicle' during short movements and hard braking" (Peters 2016, 39). Hence, the MPG multiplier ranges from 0.7 for 0% employment of trained drivers, to 1.0 for 100% employment of trained drivers.

(2) Employing Hybrid Technologies

Chapter III, Section D.3 explored the employment of hybrid technologies that are more fuel efficient; hybrid MTVRs may be able to improve fuel economy of the MTVR by up to 20% (Oshkosh Defence 2017). By replacing a percentage of the current MTVR fleet with hybrid variants, the MEU may be able to achieve greater fuel efficiency. The MPG multiplier ranges from 1.0 for 0% employment of hybrid technologies to 1.2 for 100% employment of hybrid technologies.

(3) Employing Follower Vehicle Technologies

Chapter III, Section D.4 looked at the use of UGSs that would be employed as follower vehicles for resupply operations. Fuel savings of up to 7% could be achieved through efficiencies such as automated driving, weight reduction, and reduced idling time. The MPG multiplier ranges from 1.0 for 0% employment of follower vehicle technologies, to 1.07 for 100% employment of follower vehicle technologies.

d. Communication Devices

This factor defines the employment of communication devices such as radio sets and cellphones to enable DDTs to send information on the location of isolated victims to each other, making the search for isolated victims easier and more effective. By employing communication devices, the sensor range of the DDTs will vary from the default value of 3,000m to 10,000m.

2. Noise Factors

a. Concealment

This factor defines the detectability of the isolated victims, as they may be obscured by building rubble and forested areas. The "Personal Concealment per Detection Event" parameter is used to determine the concealment factor, and it varies from 0.25 to 0.75. Unlike sensor range, the concealment factor does not vary depending on the speed of the DDT convoys.

b. Trafficability

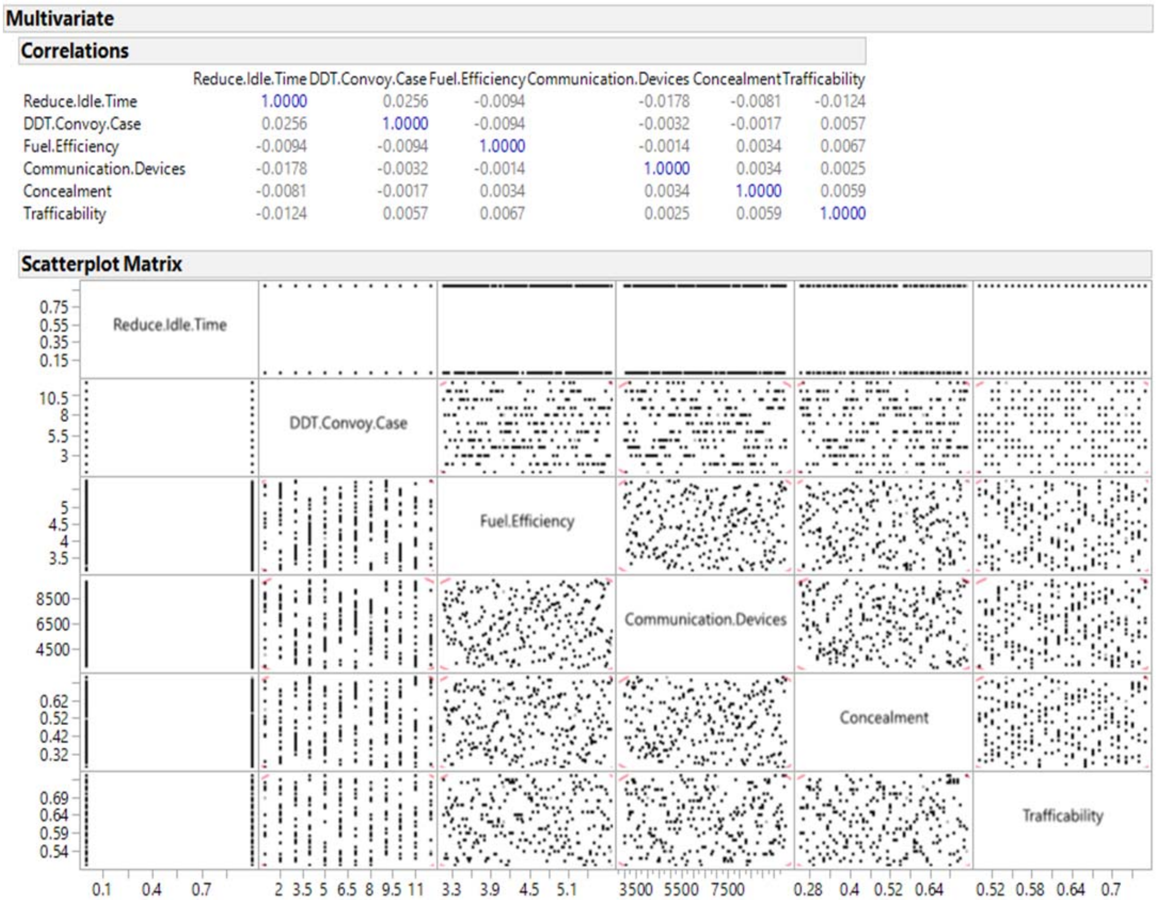
This factor defines how easy is it for the DDTs to travel on roads, as roads may be degraded or damaged due to the tsunami and earthquakes. The "Going" value in the scenario map editor in MANA is varied from 0.5 to 0.75 to simulate the various degrees of trafficability on both road and dirt.

D. EXPERIMENTAL DESIGN

As the design factors are both categorical and binary, this thesis used the NOB design technique developed by Vieira Jr. et al. (2013) to generate the design points. A design point is a unique combination of input factor values. The NOB design builds on the work of Cioppa (2002) and MacCalman (2013) to generate NOLHs for mixed designs. By using nearly orthogonal design columns, the correlation between factors remains low ($\rho \leq 0.05$), which reduces the error in the estimates of the parameter coefficients in a linear regression model. Similarly, the NOB design allows for the construction of orthogonal designs for design factors that are binary, discrete, or continuous, and which have different number of levels by using a novel linearization of the correlation calculation (Vieira Jr. et al. 2013).

Vieira et al. (2013) use stacking to ensure that the number of objects for each factor in each of its levels is equal so as to achieve balance. Balance is important because it allows for correct analysis of heteroscedastic experiments, such as the case in this research, where the design factors all have different variabilities from each other. Similar to the NOLH design technique, the NOB algorithm is also able to "efficiently explore the design space of a large number of variables in a relatively small number of runs using nearly orthogonal design columns" (Hinkson 2010, 39). While a central composite technique may also be used to generate the design points, the resulting design only includes extreme and center points. As a result, it is unable to fully explore the experimental space. By utilizing a NOB design, this thesis is able to construct the experiment space using 256 design points that are systematically and uniformly scattered throughout the design space (i.e., space-filling). The NOB design hence fulfills the desired balance and space-filling properties that good experimental designs should possess, and is suitable for this thesis where it is difficult to discern between the input factors and their interactions toward the effectiveness of HADR resupply operations.

A Microsoft Excel spreadsheet tool developed by Vieira Jr. (2012) from the Technological Institute of Aeronautics, Brazil, was used to generate the NOB design. This spreadsheet tool is able to generate designs for up to 150 factors with 256 design points (Vieira Jr. 2012). To this end, the spreadsheet tool generated a 256-point design for the input factors in Table 10. The scatterplot matrix of the experimental design is shown in Figure 19, with each box depicting the pairwise correlation between each pair of input factors. It is apparent from Figure 19. that most of the boxes are filled with data points, demonstrating the space-filling property of the NOB design. Boxes that just show straight lines correspond to input factors that are categorical or binary in nature. Even so, the design points span across their respective range of values and exhibit no signs of linear dependence. Indeed, the highest pairwise correlation between any two factors is 0.0256, as shown by the pairwise plot of variables in Figure 19. This ensures that the effects of confounding are minimized in the corresponding analysis of the data. We treat the operational plan as a discrete factor for the purposes of constructing the design, but as a categorical factor when conducting the analysis.


Multivariate

Correlations

	Reduce.Idle.Time	DDT.Convoy.Case	Fuel.Efficiency	Communication.Devices	Concealment	Trafficability
Reduce.Idle.Time	1.0000	0.0256	-0.0094	-0.0178	-0.0081	-0.0124
DDT.Convoy.Case	0.0256	1.0000	-0.0094	-0.0032	-0.0017	0.0057
Fuel.Efficiency	-0.0094	-0.0094	1.0000	-0.0014	0.0034	0.0067
Communication.Devices	-0.0178	-0.0032	-0.0014	1.0000	0.0034	0.0025
Concealment	-0.0081	-0.0017	0.0034	0.0034	1.0000	0.0059
Trafficability	-0.0124	0.0057	0.0067	0.0025	0.0059	1.0000

Figure 19. Scatterplot Matrix of the Experimental Design.

E. RUNNING THE EXPERIMENTS

1. Arithmetic Calculations

Arithmetic calculations were performed to obtain several analytical solutions in order to determine the plausibility of the simulation results. These analytical solutions do not account for stochastic elements of the HADR resupply system and operational scenario, such as locations and probabilities of detection of isolated victims, trafficability of roads, range of communication devices, and time taken to resupply victim clusters. In this thesis, mathematical calculations were performed to determine bounds on the number of victim clusters resupplied. Across all operational plans, assuming a constant fuel consumption of 4.5 MPG and fuel capacity of 78 gallons per MTVR, the maximum distance that a MTVR can travel before it has to refuel is 351 miles. By extension, the maximum distance that a DDT agent, regardless of convoy size, can travel before refueling is also 351 miles as the MTVRs travel together in a convoy. The maximum distance that a DDT agent can travel within the scenario simulation time is the product of its convoy speed and 72 hours. In this way, the number of trips that a DDT agent can make within the scenario simulation time of 72 hours can be calculated by dividing the maximum distance that it can travel within the scenario simulation time by the maximum distance that it can travel before refueling. With this information, the expected number of victim clusters that an operational plan will be able to resupply can be calculated by taking the product of (1) victim detectability rate, (2) number of trips made within 72 hours, (3) number of DDT agents, and (4) number of "ammunition" shots per DDT agent.

In the employment of operational plan 1 (see Table 11 for details on input values), there are five DDT convoys of two MTVRs each. As they travel at a speed of 30 MPH, they will be able to each cover a total of $30 \times 72 =$ 2,160 miles within the scenario simulation time of 72 hours. This translates to each DDT convoy being able to make $2{,}160 \div 351 =$ 6.15 (≈ 6) trips within 72 hours. Assuming a 50% victim detection rate, negligible loading and resupply time, and carrying capacity per DDT of 12 tons (six shots of "ammunition"), operational plan 1 will be able to resupply $0.5 \times 6 \times 5 \times 6 =$ 90 victim clusters.

In the employment of operational plan 2, there are two DDT convoys of five MTVRs each. As they travel at a speed of 15 MPH, they will be able to each cover a total of $15 \times 72 =$ 1,080 miles within the scenario simulation time of 72 hours. This translates to each DDT convoy being able to make $1{,}080 \div 351 =$ 3.07 (≈ 3) trips within 72 hours. Assuming a 50% victim detection rate, negligible loading and resupply time, and carrying capacity per DDT of 30 tons (15 shots of "ammunition"), operational plan 2 will be able to resupply $0.5 \times 3 \times 2 \times 15 =$ 45 victim clusters.

The same methodology was used to calculate the analytical solutions for all operational plans, and the result is shown in Table 13. For cases where the calculated absolute number of victim clusters resupplied was more than 100, the maximum number of victim clusters in the simulation. In reality, a higher absolute number of victim clusters resupplied may indicate that the particular operational plan may be able to resupply all victims in a time of less than 72 hours.

Table 13. Arithmetic Calculations for Number of Victims Resupplied.

Operational Plan	**Number of MTVRs Used**	**Length of DDT Convoy**	**Number of DDT Agents**	**Convoy Speed (MPH)**	**Relief Supplies per DDT (Ton)**	**No. of Victim Clusters Resupplied (Absolute)**	**No. of Victim Clusters Resupplied (Corrected)**
1	10	2	5	30	12	90	90
2	10	5	2	15	30	45	45
3	15	3	5	25	18	112.5	100
4	15	5	3	15	30	67.5	67.5
5	20	2	10	30	12	180	100
6	20	4	5	20	24	120	100
7	20	5	4	15	30	120	100
8	25	5	5	15	30	112.5	100
9	30	2	15	30	12	270	100
10	30	3	10	25	18	225	100
11	30	5	6	15	30	135	100
12	30	6	5	10	36	90	90

An analysis of the arithmetic calculations indicates that, within the existing operational plans considered in this thesis, the plans that utilize a minimum of 20 MTVRs have the greatest chance of success. An additional insight gleaned was that the combination of convoy speed and operational plan has a larger influence on number of victims resupplied, than the amount of relief supplies carried by each DDT convoy. This is evident when comparing within the operational plans that utilized the same number of MTVRs, such as: (1) operational plans 1 and 2; (2) operational plans 3 and 4; (3)

operational plans 5, 6 and 7; and (4) operational plans 9, 10, 11 and 12. The operational plans that deployed shorter DDT convoys at faster speeds were more effective than their counterparts that deployed larger DDT convoys at slower speeds. Indeed, such is the joint importance of speed and convoy size that operational plan 1, which only utilizes 10 MTVRs travelling at 30 MPH, is able to match the performance of operational plan 12, which utilizes 30 MTVRs travelling at 10 MPH.

From these 12 operational plans, it is not possible to determine how much of the performance gains for shorter DDT convoys are due to speed alone, and how much are due to the fact that there are a greater number of convoys operating independently. This could be examined in future experiments

2. First Phase Experiment

A first phase experiment was performed as a means to "screen" the input factors quickly and efficiently, and isolate factors that dominate. This was carried out by performing 40 replications on the 256-point design matrix, generating a total of 10,240 simulation runs. Each replication used a random starting seed. The first phase experiment took about four hours to complete on a high performance computing cluster. To investigate the effects of the input factors on the data response, we first summarize the data by computing the mean responses over all replications for each of the 256 design points. We then determine the most important factors using second-order stepwise regression models that considered all main, quadratic, and two-way interaction terms.

a. Number of Victim Clusters Resupplied

The first data response to be investigated is the number of victim clusters resupplied, as it addresses the MOE of how effective is each capability instantiation toward the throughput of relief supplies to disaster areas. The summary of fit for the regression model is shown in Figure 20. ; it shows a high adjusted R^2 value of 0.98. This means that the fitted regression model is suitable for analyzing the number of victims resupplied.

Summary of Fit	
RSquare	0.986028
RSquare Adj	0.984235
Root Mean Square Error	2.141242
Mean of Response	72.98242
Observations (or Sum Wgts)	256

Figure 20. Summary of Fit for Number of Victim Clusters Resupplied (First Phase Experiment).

This is confirmed by the “actual vs. predicted” plot as shown in Figure 21, where we see that most of the data lie close to the fitted line, with narrow confidence bands.

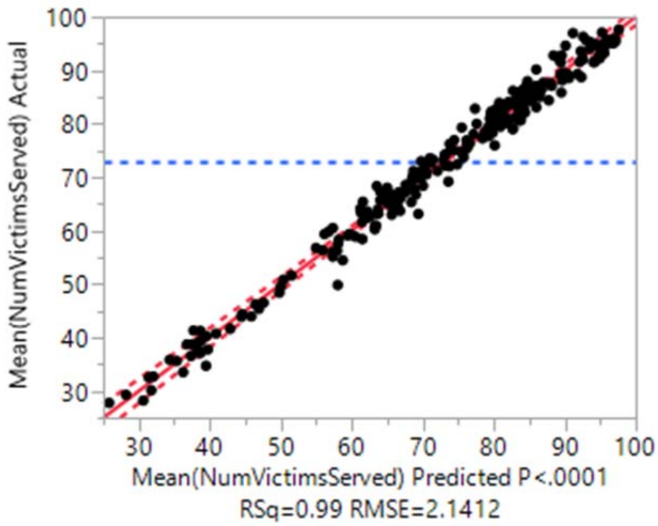


Figure 21. Actual vs. Predicted Plot for Number of Victim Clusters Resupplied (First Phase Experiment).

The prediction profiler for the regression model can be used interactively to show the effect that the respective input factors have on the number of victim clusters resupplied; a snapshot of the profiler is shown in Figure 22. Initial analysis shows that the “Operational Plan” and “Communication Devices” factors dominate the other factors in terms of number of victims resupplied. This is further illustrated by the effect summary in Figure 23, which shows that the aforementioned two factors indeed dominate all other factors and interactions. The model has nine terms: five main effects, two quadratics, and two interaction terms. Simplifying it to a model that includes only the four terms associated with “Operational Plan” and “Communication Devices” would still achieve a high adjusted R^2 value of 0.96. Through the rest of this thesis, we report the models that come from fitting stepwise regression without any further simplification because we are focusing on the largest effects.

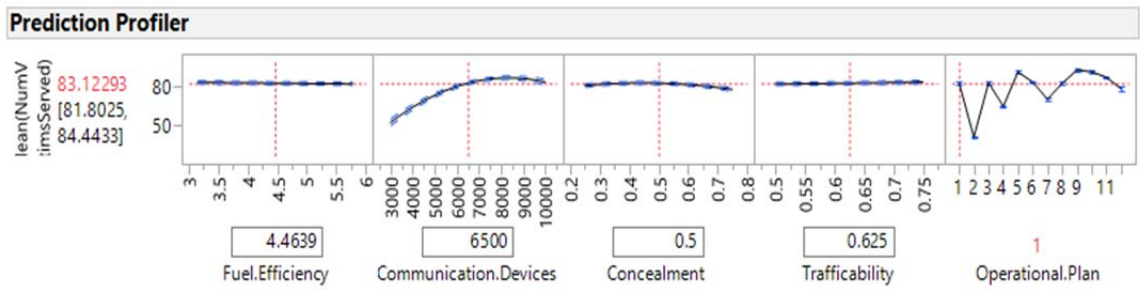


Figure 22. Prediction Profiler for Number of Victim Clusters Resupplied (First Phase Experiment).

Effect Summary

Source	LogWorth	PValue
Operational.Plan	185.247	0.00000
Communication.Devices	107.581	0.00000
Communication.Devices*Communication.Devices	80.582	0.00000
Operational.Plan*Communication.Devices	41.308	0.00000
Concealment*Concealment	11.699	0.00000
Concealment	9.448	0.00000 ^
Trafficability	2.977	0.00105
Fuel.Efficiency	1.966	0.01082
Concealment*Trafficability	1.220	0.06025

Figure 23. Effect Summary for Number of Victim Clusters Resupplied (First Phase Experiment).

b. Number of Times That the DDT Convoys Were in a “Fuel Out” State

In this modeling effort, we attempted to use weapons in MANA as counting mechanisms. As one example, in order to acquire a count of the total number of times that DDT agents entered the “fuel out” state, each DDT was given a special weapon that was only capable of shooting at a particular class of dummy target agent when it first entered the “fuel out” state. This particular dummy target agent class was only visible to a DDT agent entering the “fuel out” state, and was configured such that it would never die, it would just keep accruing hits. The weapon that the DDT used for this had only one shot of ammunition in it, with a long reload time, such that it would not fire more than one shot of this type on the same instance of the "fuel out" state. Using this method, we intended to interpret the total number of hits on the target agent as the total number of times that DDT agents entered the "fuel out" state. However, we became aware of two examples of misfiring that made the counter-based metrics in MANA to be unreliable for analysis. Instead, we use an analytically-derived measure as described in Chapter IV, Section B for fuel consumption. Fortunately, the total number of victims served and the probability of serving 50%, 75%, and 100% of the victims, as well as the time required to serve these percentages, were not affected by this error.

3. Second Phase Experiment

The first phase experiment identified "Operational Plan" as a strongly dominant factor. This can be explained by noting that this factor controls the number of MTVRs used in a simulation run, as well as the speed and sensor range of the MTVRs; the more MTVRs used and the greater distance they travel, the more victims one can expect to be resupplied. At the same time, the more MTVRs used and the faster they travel, the more fuel will be consumed. In order to achieve a more balanced analysis, the second phase experiment will only consider operational plans that use 30 MTVRs; this will reduce the number of operational plans to four. In doing so, the effect of the number of MTVRs used will be removed from the model. Instead, the effect of DDT convoy length will be explored in greater detail, since convoy length affects: (1) speed, (2) sensor range factor, (3) supplies carried, and (4) number of DDT agents used to represent the 30 MTVRs. With an equal number of MTVRs for all simulation runs, the results for the second phase experiment should be less biased toward the choice of operational plan and provide more insights into which OE factor contributes more toward increasing operational reach. The four operational plans to be used in the second phase experiment are listed in Table 14.

Table 14. Operational Plans Used in Second Phase Experiment.

Operational Plan	Number of MTVRs Used	Length of DDT Convoy	Number of DDT Agents	Convoy Speed (MPH)	Relief Supplies per DDT (Ton)	Sensor Range Factor
1	30	2	15	30	12	0.80
2	30	3	10	25	18	0.85
3	30	5	6	15	30	0.95
4	30	6	5	10	36	1.00

The second phase experiment was carried out by performing 100 replications on the 256-point design matrix, generating a total of 25,600 simulation runs. Each replication used a random starting seed, and the second phase experiment took about nine hours to complete on a high performance computing cluster.

V. DATA ANALYSIS

The second phase experiment involved a total of 25,600 simulation runs and generated a large amount of data. Similar to the first phase experiment, partition trees and second-order stepwise regression models that considered all main, quadratic, and two-way interaction terms were once again used to investigate the effects of the input factors on the MOEs.

A. DATA SUMMARY OF SECOND PHASE EXPERIMENT

A basic statistical summary of the data requirements listed in Table 9 is presented in this section. Preliminary analysis of the raw data will provide insights into the validity of the data prior to subsequent detailed analysis. The histograms presented in this section contain data from all 25,600 simulation runs to show the range of all simulation results, and summarized data that show the range of potential outcomes for the 256 design points.

1. Number of Victim Clusters Resupplied

Out of 25,600 simulation runs, the maximum number of victim clusters resupplied is 100, and the minimum number of victim clusters resupplied is 12. The histogram is shown in Figure 24.

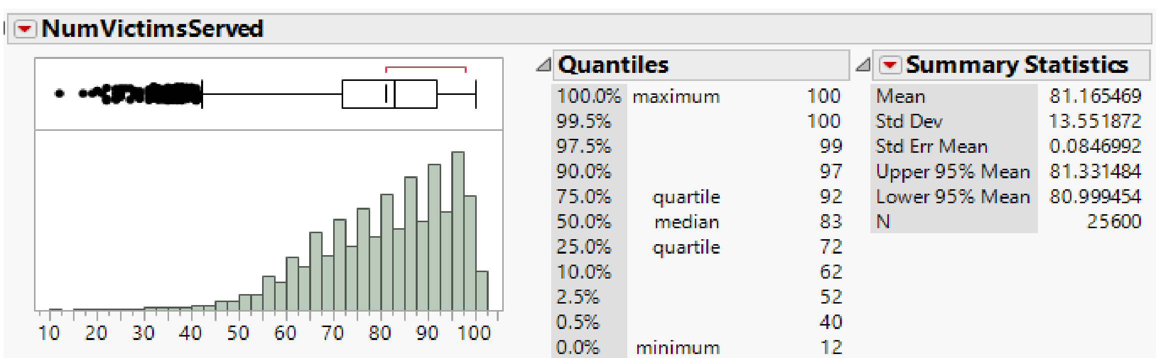
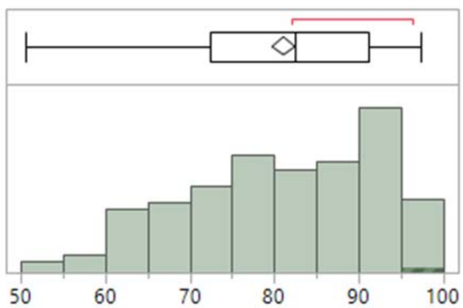


Figure 24. Histogram for Number of Victim Clusters Resupplied (Second Phase Experiment).

Raw data such as those in Figure 24. can be used to check the overall range of results, but we are also interested in the behavior for each design point. Summarizing the data over replications allows us to look at the average number of victim clusters resupplied by design point. To this end, each design point for the number of victim clusters resupplied is summarized by its mean, and the histogram shown in Figure 25. indicate a wide range of outcomes, with a minimum mean number of 50.45 victim clusters resupplied and a maximum mean number of 97.31 victim clusters resupplied.

Mean(NumVictimsServed)



Quantiles

100.0%	maximum	97.31
99.5%		97.253
97.5%		96.2875
90.0%		94.59
75.0%	quartile	91.1575
50.0%	median	82.485
25.0%	quartile	72.3625
10.0%		64.727
2.5%		58.21325
0.5%		51.42755
0.0%	minimum	50.45

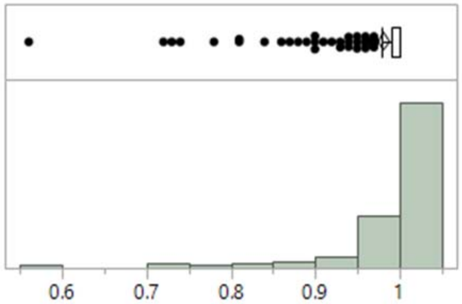
Summary Statistics

Mean	81.165469
Std Dev	11.239063
Std Err Mean	0.7024414
Upper 95% Mean	82.548794
Lower 95% Mean	79.782143
N	256

Figure 25. Histogram for Mean Number of Victim Clusters Resupplied (Second Phase Experiment).

2. Number of Cases Where 50% of Victim Clusters Were Resupplied

Out of 25,600 simulation runs, the number of cases where 50% of victim clusters were resupplied is 25,138, so it is achieved in the vast majority of simulation runs. For each design point, the proportion of replication where 50% of victim clusters are resupplied is computed. The histogram in Figure 26 shows that the mean probability of success in resupplying 50% of victim clusters is 0.98, but the least effective design point only achieved this threshold in 56 of the 100 replications.



Quantiles

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		1
75.0%	quartile	1
50.0%	median	1
25.0%	quartile	0.99
10.0%		0.95
2.5%		0.81
0.5%		0.6056
0.0%	minimum	0.56

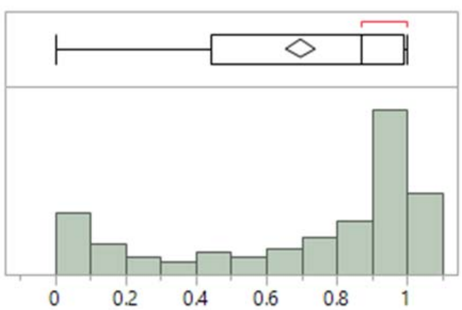
Summary Statistics

Mean	0.9819531
Std Dev	0.050783
Std Err Mean	0.0031739
Upper 95% Mean	0.9882036
Lower 95% Mean	0.9757027
N	256

Figure 26. Histogram for the Estimated Probability that 50% of Victim Clusters Were Resupplied (Second Phase Experiment).

3. Number of Cases where 75% of Victim Clusters Were Resupplied

Using the approach of Section V.A.2 yields the estimated probability of resupplying 75% of victim clusters for each design point, and the histogram is shown in Figure 27. It shows that the mean probability of success in resupplying 75% of victim clusters is 0.70, but the least effective design point only achieved this threshold in none of the 100 replications.



Quantiles

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		1
75.0%	quartile	0.99
50.0%	median	0.87
25.0%	quartile	0.4425
10.0%		0.064
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics

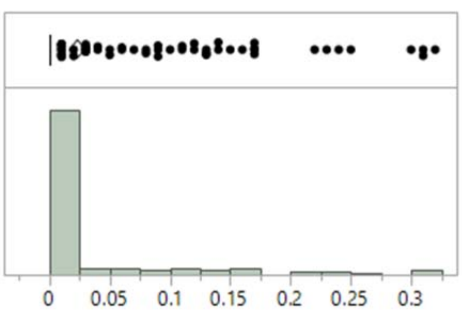
Mean	0.6974219
Std Dev	0.3527288
Std Err Mean	0.0220456
Upper 95% Mean	0.7408364
Lower 95% Mean	0.6540073
N	256

Figure 27. Histogram for the Estimated Probability that 75% of Victim Clusters Were Resupplied (Second Phase Experiment).

4. Number of Cases where 100% of Victim Clusters Were Resupplied

Lastly, a similar approach yields the estimated probability of resupplying 100% of victim clusters for each design point, and the histogram is shown in Figure 28. It shows that the mean probability of success in resupplying 100% of victim clusters is only 0.02.

This illustrates the difficulty of a resupply operation in an HADR scenario, mainly due to the dispersion of victim clusters, and difficulty in searching for them.



Quantiles

100.0%	maximum	0.32
99.5%		0.31715
97.5%		0.23575
90.0%		0.1
75.0%	quartile	0
50.0%	median	0
25.0%	quartile	0
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics

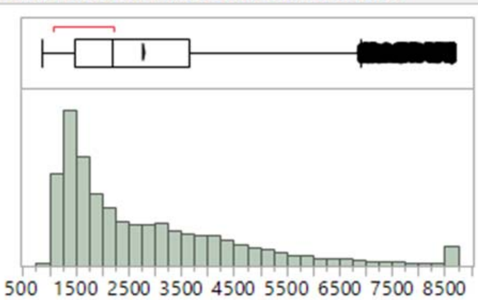
Mean	0.0231641
Std Dev	0.0598278
Std Err Mean	0.0037392
Upper 95% Mean	0.0305278
Lower 95% Mean	0.0158003
N	256

Figure 28. Histogram for the Estimated Probability that 100% of Victim Clusters Were Resupplied (Second Phase Experiment).

5. Lower Bound for Time Taken to Resupply 50% of Victim Clusters

Out of 25,600 simulation runs, there were 462 cases where less than 50% of victim clusters were resupplied; it is evident that these cases take more than 72 hours to resupply 50% of victim clusters. For each of these 462 cases, we replace the missing value for the time taken to resupply 50% of victim clusters with 8,640, the number of time steps that it takes to represent 72 hours. Having done that, the histogram is shown in Figure 29. The reader may notice a small spike to the right tail of the histogram: these are the 462 cases that took more than 72 hours to resupply 50% of victim clusters.

LowerBoundTime50%VictimsServed



Quantiles

100.0%	maximum	8640
99.5%		8640
97.5%		7745.925
90.0%		5095
75.0%	quartile	3651.75
50.0%	median	2185.5
25.0%	quartile	1479
10.0%		1253
2.5%		1117
0.5%		1036
0.0%	minimum	857

Summary Statistics

Mean	2788.9607
Std Dev	1699.9652
Std Err Mean	10.624783
Upper 95% Mean	2809.7859
Lower 95% Mean	2768.1355
N	25600

Figure 29. Histogram for Lower Bound on Time Taken to Resupply 50% of Victim Clusters (Second Phase Experiment).

Each design point is then summarized by its mean, and the histogram of these 256 means, each of which is an estimate of the time taken to resupply 50% of victim clusters, is shown in Figure 30. The results indicate a wide range of outcomes, with a minimum mean time taken of 9.89 hours and a maximum mean time taken of 60.28 hours.

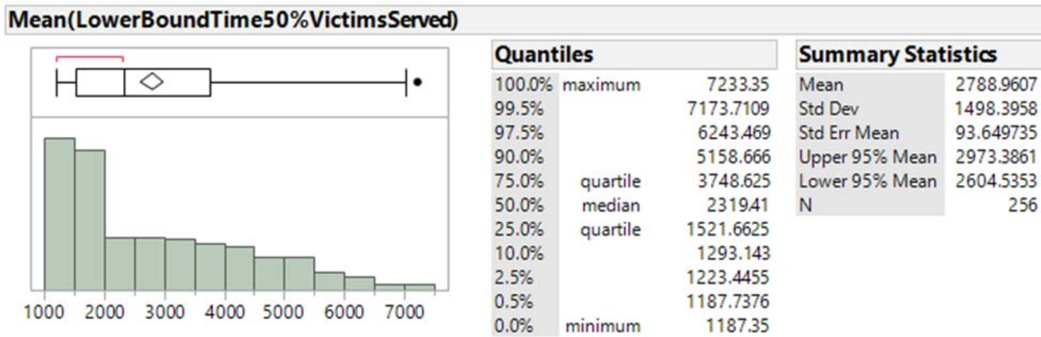


Figure 30. Histogram for Mean Lower Bound on Time Taken to Resupply 50% of Victim Clusters (Second Phase Experiment).

6. Lower Bound for Time Taken to Resupply 75% of Victim Clusters

Out of 25,600 simulation runs, there were 7,746 cases where less than 75% of victim clusters were resupplied; it is evident that they take more than 72 hours to resupply 75% of victim clusters. For each of these 7,746 cases, we replace the missing value for the time taken to resupply 75% of victim clusters with 8,640, the number of time steps that it takes to represent 72 hours. Having done that, the histogram is shown in Figure 31. The reader may notice that the spike in the right tail of the histogram is now even higher, reflecting the increased number of cases where it took more than 72 hours to resupply 75% of victim clusters.

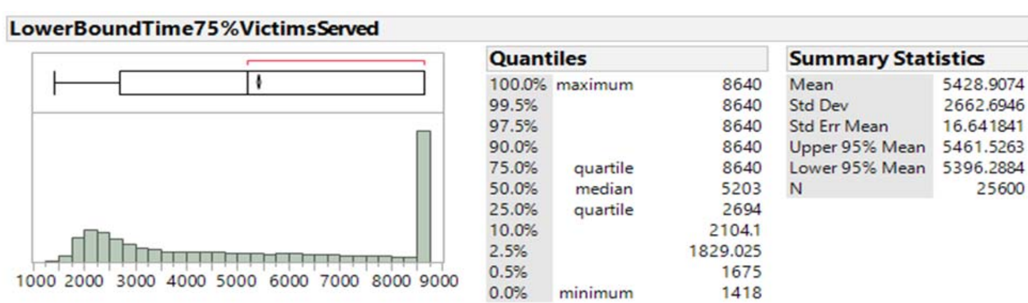
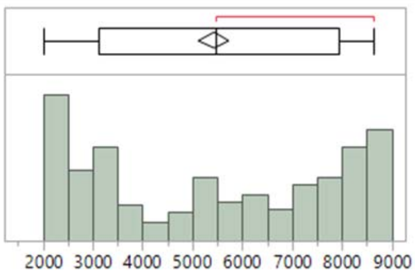


Figure 31. Histogram for Lower Bound on Time Taken to Resupply 75% of Victim Clusters (Second Phase Experiment).

Each design point is then summarized by its mean, and the histogram of these 256 means, each of which is an estimate of the time taken to resupply 75% of victim clusters, is shown in Figure 32. The results indicate a wide range of outcomes, with a minimum mean time taken of 16.79 hours and a maximum mean time taken of 72.00 hours.

Mean(LowerBoundTime75%VictimsServed)



Quantiles

100.0%	maximum	8640
99.5%		8640
97.5%		8640
90.0%		8553.902
75.0%	quartile	7939.7475
50.0%	median	5469.99
25.0%	quartile	3108.2375
10.0%		2288.222
2.5%		2088.92675
0.5%		2023.0603
0.0%	minimum	2015.2

Summary Statistics

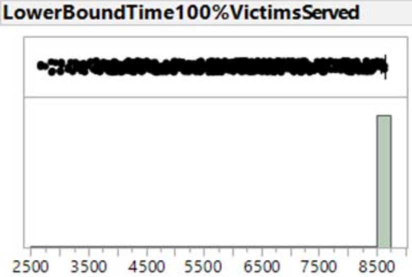
Mean	5428.9074
Std Dev	2398.595
Std Err Mean	149.91219
Upper 95% Mean	5724.131
Lower 95% Mean	5133.6837
N	256

Figure 32. Histogram for Mean Lower Bound on Time Taken to Resupply 75% of Victim Clusters (Second Phase Experiment).

7. Lower Bound for Time Taken to Resupply 100% of Victim Clusters

Out of 25,600 simulation runs, there are 25,007 cases where less than 100% of victim clusters were resupplied; it is evident that they take more than 72 hours to resupply 100% of victim clusters. For each of these 25,007 cases, we replace the missing value for the time taken to resupply 75% of victim clusters with 8,640, the number of time steps that it takes to represent 72 hours. Having done that, the histogram is shown in Figure 33. The reader may notice that almost all the data is concentrated in the right tail of the histogram, illustrating that most cases require more than 72 hours to resupply 100% of victim clusters, and it confirms the difficulty in resupplying 100% of victim clusters.

LowerBoundTime100%VictimsServed



Quantiles

100.0%	maximum	8640
99.5%		8640
97.5%		8640
90.0%		8640
75.0%	quartile	8640
50.0%	median	8640
25.0%	quartile	8640
10.0%		8640
2.5%		8640
0.5%		4546.03
0.0%	minimum	2673

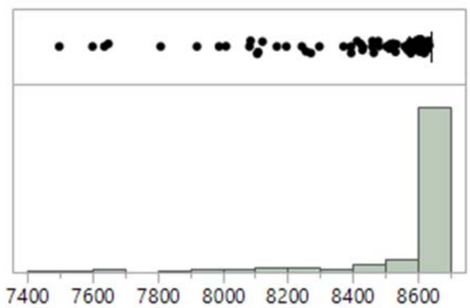
Summary Statistics

Mean	8577.2381
Std Dev	465.51363
Std Err Mean	2.9094602
Upper 95% Mean	8582.9408
Lower 95% Mean	8571.5354
N	25600

Figure 33. Histogram for Lower Bound on Time Taken to Resupply 100% of Victim Clusters (Second Phase Experiment).

Each design point is then summarized by its mean, and the histogram of these 256 means, each of which is an estimate of the time taken to resupply 100% of victim clusters, is shown in Figure 34. The results indicate a narrow range of outcomes, with a minimum mean time taken of 62.47 hours and a maximum mean time taken of 72.00 hours.

Mean(LowerBoundTime100%VictimsServed)



Quantiles

100.0%	maximum	8640
99.5%		8640
97.5%		8640
90.0%		8640
75.0%	quartile	8640
50.0%	median	8640
25.0%	quartile	8640
10.0%		8432.29
2.5%		7950.03825
0.5%		7525.9039
0.0%	minimum	7496.68

Summary Statistics

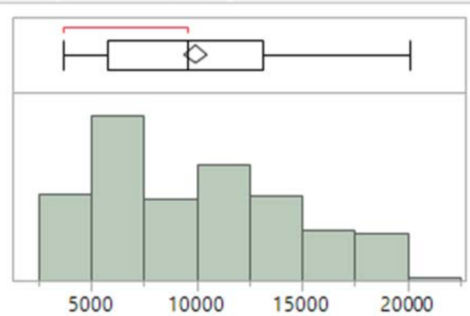
Mean	8577.2381
Std Dev	182.23451
Std Err Mean	11.389657
Upper 95% Mean	8599.6679
Lower 95% Mean	8554.8084
N	256

Figure 34. Histogram for Mean Lower Bound on Time Taken to Resupply 100% of Victim Clusters (Second Phase Experiment).

8. Fuel Consumed

Similarly, by first computing the fuel consumed per victim cluster resupplied for each simulation run and then summarizing this value by its mean for each design point, the histogram of mean fuel consumed is shown in Figure 35. The results indicate a wide range of outcomes, with a minimum of 3,687 gallons of fuel consumed and a maximum of 20,076 gallons of fuel consumed.

Mean(FuelConsumed)



Quantiles

100.0%	maximum	20076.170886
99.5%		20051.081742
97.5%		19543.830543
90.0%		16347.884602
75.0%	quartile	13157.396447
50.0%	median	9591.9437198
25.0%	quartile	5782.9723041
10.0%		4490.0415039
2.5%		3953.8408125
0.5%		3690.9577915
0.0%	minimum	3687.4090121

Summary Statistics

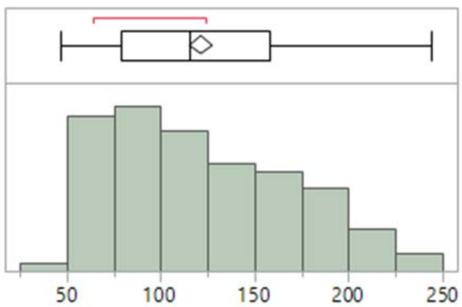
Mean	9933.2497
Std Dev	4526.3547
Std Err Mean	282.89717
Upper 95% Mean	10490.362
Lower 95% Mean	9376.1373
N	256

Figure 35. Histogram for Mean Fuel Consumed (Second Phase Experiment).

9. Fuel Consumed Per Victim Cluster Resupplied

Similarly, by summarizing each design point by its mean, the histogram for the mean fuel consumed per victim cluster resupplied is shown in Figure 36. The results also indicate a wide range of outcomes, with a minimum of 46 gallons of fuel consumed and a maximum of 245 gallons of fuel consumed per victim cluster resupplied.

Mean(FuelConsumedPerVictimResupplied)



Quantiles

100.0%	maximum	244.74894567
99.5%		242.70598433
97.5%		223.57326208
90.0%		194.56493526
75.0%	quartile	158.24420066
50.0%	median	115.53594055
25.0%	quartile	78.415863298
10.0%		64.790745916
2.5%		54.035851175
0.5%		46.787293945
0.0%	minimum	46.057056495

Summary Statistics

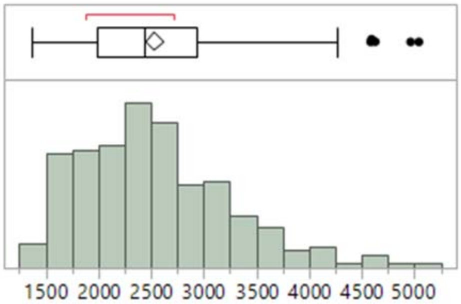
Mean	121.65424
Std Dev	48.528825
Std Err Mean	3.0330516
Upper 95% Mean	127.62726
Lower 95% Mean	115.68122
N	256

Figure 36. Histogram for Mean Fuel Consumed per Victim Cluster Resupplied (Second Phase Experiment).

10. Lower Bound for Fuel Consumed to Resupply 50% of Victim Clusters

In Section A.5, it was seen that out of 25,600 simulation runs, there were 462 cases where less than 50% of victim clusters were resupplied within 72 hours. For each these 462 cases, we calculate the amount of fuel that they consumed in 72 hours analytically using the formula presented in Chapter IV, Section B, and add it to the fuel consumed by the 25,138 cases where 50% of victim clusters were resupplied within 72 hours. Each design point is then summarized by its mean, and the histogram for the mean fuel consumed to resupply 50% of victim clusters is shown in Figure 37. The results indicate a wide range of outcomes, with a minimum mean fuel consumed of 1,360 gallons and a maximum mean fuel consumed of 5,043 gallons to resupply 50% of victim clusters.

Mean(LowerBoundFuel50%VictimsServed)



Quantiles

100.0%	maximum	5042.7058824
99.5%		5020.3815809
97.5%		4236.3560108
90.0%		3494.1593506
75.0%	quartile	2932.3401261
50.0%	median	2435.3931249
25.0%	quartile	1984.0613949
10.0%		1698.823588
2.5%		1513.2900227
0.5%		1371.9371068
0.0%	minimum	1359.9627561

Summary Statistics

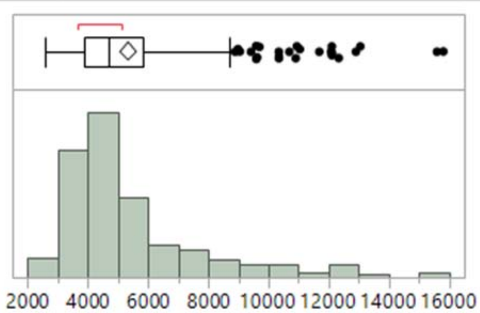
Mean	2535.2842
Std Dev	707.34685
Std Err Mean	44.209178
Upper 95% Mean	2622.3458
Lower 95% Mean	2448.2226
N	256

Figure 37. Histogram for Mean Lower Bound Fuel Consumed to Resupply 50% of Victim Clusters (Second Phase Experiment).

11. Lower Bound for Fuel Consumed to Resupply 75% of Victim Clusters

In Section A.6, it was seen that out of 25,600 simulation runs, there were 7,746 cases where less than 75% of victim clusters were resupplied within 72 hours. For each these 7,746 cases, we calculate the amount of fuel that they consumed in 72 hours analytically using the formula presented in Chapter IV, Section B, and add it to the fuel consumed by the 17,854 cases where 75% of victim clusters were resupplied within 72 hours. Each design point is then summarized by its mean, and the histogram for the mean fuel consumed to resupply 75% of victim clusters is shown in Figure 38. The results indicate a wide range of outcomes, with a minimum mean fuel consumed of 2,592 gallons and a maximum mean fuel consumed of 15,818 gallons to resupply 75% of victim clusters.

Mean(LowerBoundFuel75%VictimsServed)



Quantiles

100.0%	maximum	15818.136161
99.5%		15757.881444
97.5%		12110.701071
90.0%		8742.3947403
75.0%	quartile	5841.9393105
50.0%	median	4667.3702563
25.0%	quartile	3870.4493969
10.0%		3311.3760891
2.5%		2966.6606909
0.5%		2622.4271837
0.0%	minimum	2592.3929236

Summary Statistics

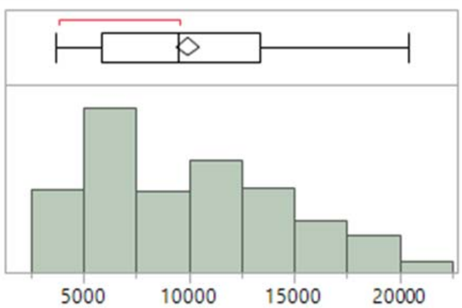
Mean	5346.4012
Std Dev	2347.3874
Std Err Mean	146.71171
Upper 95% Mean	5635.3221
Lower 95% Mean	5057.4802
N	256

Figure 38. Histogram for Mean Lower Bound Fuel Consumed to Resupply 75% of Victim Clusters (Second Phase Experiment).

12. Lower Bound for Fuel Consumed to Resupply 100% of Victim Clusters

In Section A.7, it was seen that out of 25,600 simulation runs, there were 25,007 cases where less than 100% of victim clusters were resupplied within 72 hours. For each these 25,007 cases, we calculate the amount of fuel that they consumed in 72 hours analytically using the formula presented in Chapter IV, Section B, and add it to the fuel consumed by the 593 cases where 100% of victim clusters were resupplied within 72 hours. Each design point is then summarized by its mean, and the histogram for the mean fuel consumed to resupply 100% of victim clusters is shown in Figure 39. The results indicate a wide range of outcomes, with a minimum mean fuel consumed of 3,687 gallons and a maximum mean fuel consumed of 20,379 gallons to resupply 100% of victim clusters.

Mean(LowerBoundFuel100%VictimsServed)



Quantiles

100.0%	maximum	20379.369085
99.5%		20378.796066
97.5%		19439.366279
90.0%		16507.592349
75.0%	quartile	13322.641586
50.0%	median	9483.1615639
25.0%	quartile	5799.7444475
10.0%		4526.8782315
2.5%		3953.8408125
0.5%		3707.1061393
0.0%	minimum	3687.4090121

Summary Statistics

Mean	9932.2129
Std Dev	4510.9437
Std Err Mean	281.93398
Upper 95% Mean	10487.428
Lower 95% Mean	9376.9973
N	256

Figure 39. Histogram for Mean Lower Bound Fuel Consumed to Resupply 100% of Victim Clusters (Second Phase Experiment).

B. ANALYSIS OF SECOND PHASE EXPERIMENT

Partition tree models were used to investigate the effects of the input factors on the MOEs as identified in Chapter IV, Section B. Partition tree models are a "nonparametric approach to fitting a response to a set of data" (Kleijnen et al. 2005, 284), and are a relatively intuitive way of exploring the effect of input variables on a response variable. A partition tree model is constructed by splitting the simulation data recursively into groups with different means and lower standard deviations (branches) until a desired R^2 value is achieved. The higher the R^2 value, the more variability in the data that is explained by the partition tree model, and thus the better the model fit. In the subsequent analysis, the partition tree models were constructed using average results across the replications for each design point.

1. Throughput of Relief Supplies to Isolated Victims

The first MOE to be investigated is the throughput of relief supplies to isolated victims, and a partition tree was constructed using the number of victim clusters resupplied as the response, as shown in Figure 40. The findings reveal that shorter and faster DDT convoys that are able to communicate with one another are more effective toward the throughput of relief supplies to isolated victims. Interestingly, the first split was on the “Communications Devices” factor, and not the “Operational Plan” factor as in the first phase experiment. This shows that the screening efforts to remove dominant factors were effective for this MOE. Specifically, when the use of communication devices is able to increase the sensor range to more than 4,455 meters, the mean number of victim clusters resupplied is 84.79. This finding shows that the use of communications devices is crucial in passing on valuable information between DDT convoys searching for isolated victims; the farther the range of the sensor, the better.

The second split divided the “Operational Plan” factor into operational plan 4 against operational plans 1, 2, and 3. In this case, when operational plan 4 was utilized, the mean number of victims resupplied is 73.25. When operational plans 1, 2, and 3 were utilized, the mean number of victim clusters resupplied is 88.87. With reference to the DDT convoy length of the different operational plans shown in Table 14, this finding reveals that operational plans with shorter and faster convoys are more effective in resupplying isolated victims. This could be due to the fact that shorter convoys translate to a greater number of DDT agents exploring more areas of the map simultaneously; at the same time, they are also able to travel quicker to LDCs for reloading, hence minimizing the penalty of running out of relief supplies more frequently.

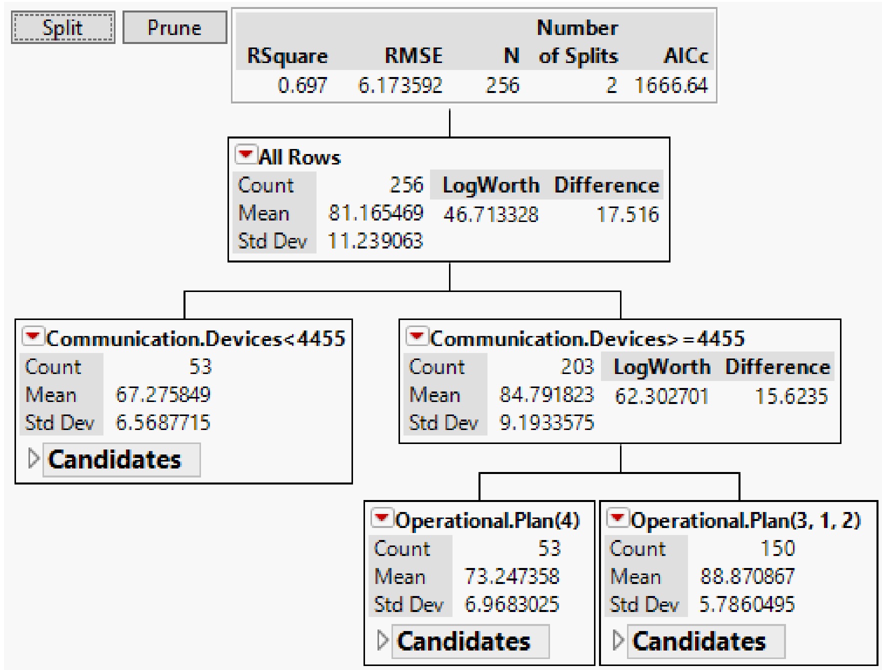


Figure 40. Partition Tree for Number of Victim Clusters Resupplied (Second Phase Experiment).

A second-order stepwise regression model for the number of victim clusters resupplied was constructed to explore the interactions between the factors, and the interaction profiles for the input factors that affect the number of victim clusters resupplied is shown in Figure 41. On the interaction plot of "Fuel Efficiency" and "Trafficability," we see that when trafficability is bad (0.5), an increase in fuel efficiency increases the number of victims resupplied. On the interaction plot of "Fuel Efficiency" and "Operational Plan," we see that an increase in fuel efficiency is able to increase the number of victim clusters resupplied in operational plan 4, which is the case where the speed of the DDTs was the slowest. This demonstrates that fuel efficiency becomes a concern in situations where the trafficability of roads is bad or when the DDT convoys are slow; fuel efficiency does not have as much of an impact in situations where the trafficability of roads is good or when the DDT convoys are fast. The reader is reminded that fuel efficiency is not affected by the speed of the DDTs due to their relatively low speed; this was explained earlier in Chapter III, Section G.4.11.

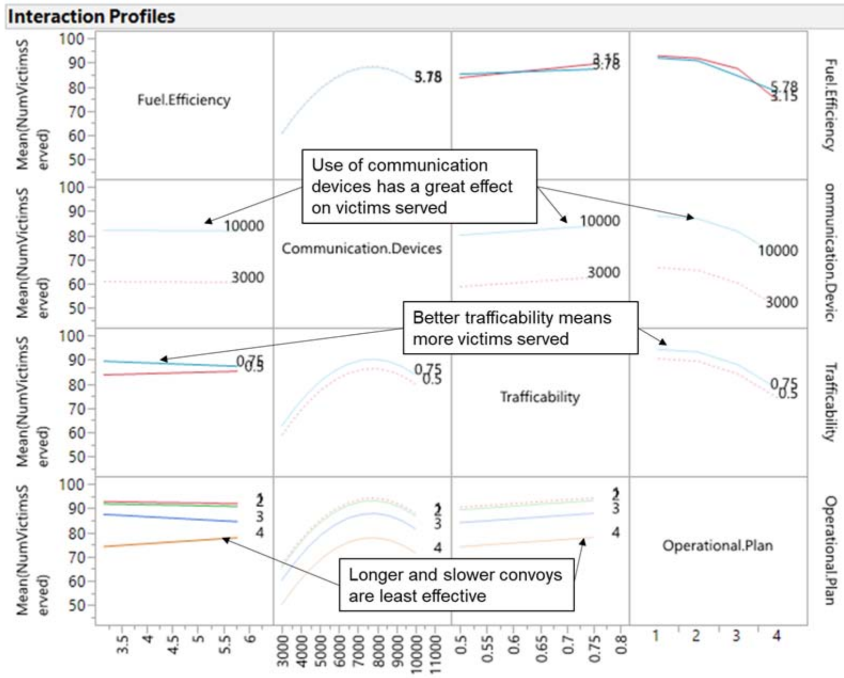


Figure 41. Interaction Profiles for Input Factors that Affect the Number of Victim Clusters Resupplied (Second Phase Experiment).

2. Timeliness in Delivering Relief Supplies to Isolated Victims

The second MOE to be investigated is the timeliness in delivering relief supplies to isolated victims. Three partition trees were constructed, using the lower bound time taken to resupply: (1) 50%, (2) 75%, and (3) 100% of victim clusters, respectively, as the responses. The effects summary table is shown in Table 15, with detailed explanation in Sections a, b, and c.

Table 15. Effects Summary Table for Partition Trees for Lower Bound Time Taken to Resupply 50/75/100% of Victim Clusters (Second Phase Experiment).

Input Factors	**Lower Bound for Time Taken to Resupply**		
	50% of Victims	**75% of victims**	**100% of Victims**
Operational Plan	√	√	√
Reduce Idle Time	-	-	-
Fuel Efficiency	-	-	-
Communication Devices	-	√	√
R^2 of Partition Tree	**0.831**	**0.791**	**0.640**

a. Lower Bound for Time Taken to Resupply 50% of Victim Clusters

The "Operation Plan" factor had the greatest effect on the lower bound time taken to resupply 50% of victim clusters. As shown in the partition tree in Figure 42, the first split was on the "Operational Plan" factor. Subsequent splits in the partition tree were similar, splitting at the different operational plans. Specifically, operational plan 1 took the least amount of time at 11.72 hours, while operational plan 4 took the most amount of time at 39.82 hours. This shows that the "Operational Plan" factor strongly affects the time taken to resupply 50% of victim clusters. In particular, operational plans that utilize shorter and faster convoys were able to resupply 50% of victim clusters the quickest.

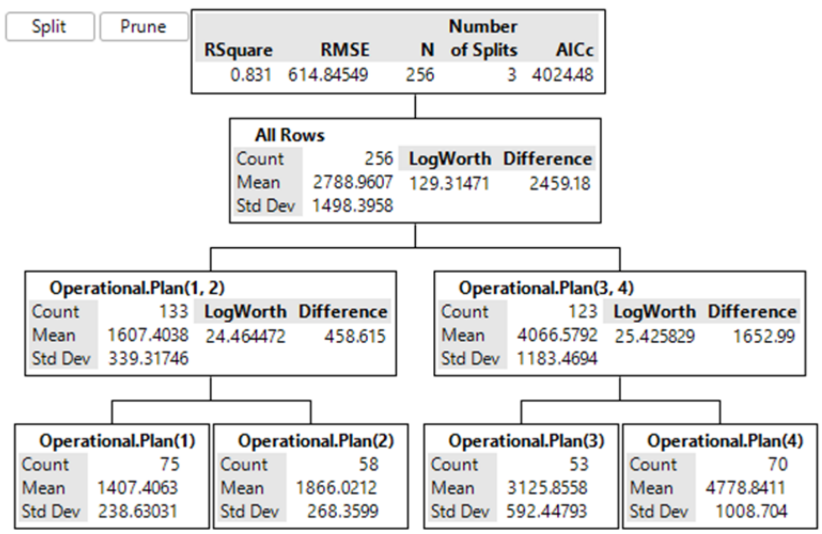


Figure 42. Partition Tree for Lower Bound Time Taken to Resupply 50% of Victim Clusters (Second Phase Experiment).

b. Lower Bound for Time Taken to Resupply 75% of Victim Clusters

Both "Operational Plan" and "Communication Devices" factors had a large effect on the lower bound time taken to resupply 75% of victim clusters. Similar to Section B.2.a, the first split divided the "Operational Plan" factor into operational plans 1 and 2 against operational plans 3 and 4. The second split divided the "Communication Devices" factor for operational plans 1 and 2. These findings show that shorter and faster DDT convoys that are adept at communicating across long distances (≥ 4,675 meters) are able to resupply 75% of victim clusters in the shortest amount of time at 23.62 hours. The partition tree for the time taken to resupply 75% of victim clusters is shown in Figure 43.

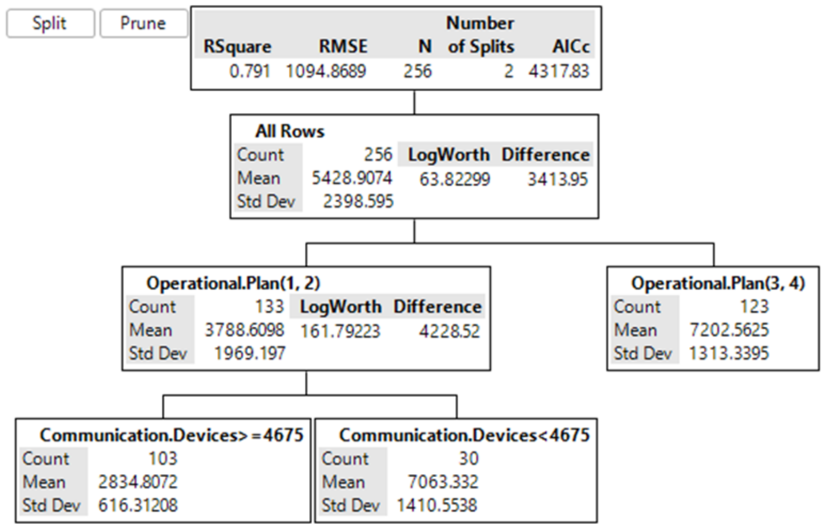


Figure 43. Partition Tree for Lower Bound Time Taken to Resupply 75% of Victim Clusters (Second Phase Experiment).

c. *Lower Bound for Time Taken to Resupply 100% of Victim Clusters*

Both "Operational Plan" and "Communication Devices" factors had a large effect on the lower bound time taken to resupply 100% of victim clusters. As shown in the partition tree in Figure 44, both the first and second splits were on the "Communication Device" factor. The third split was on the "Operational Plan" factor. These findings show that shorter and faster DDT convoys that are adept at communicating across long distances (≥ 8,518 meters) are able to resupply 100% of victim clusters quickest. However, the time taken to resupply 100% of victim clusters do not differ much between the different leaves of the partition tree, with the shortest amount of time at 68.23 hours, and the most amount of time at 72 hours. This shows that: (1) both "Operational Plan" and "Communication Devices" factors strongly affect the time taken to resupply 100% of victim clusters, and (2) a certain minimum time duration is required if 100% of victim clusters are to be resupplied.

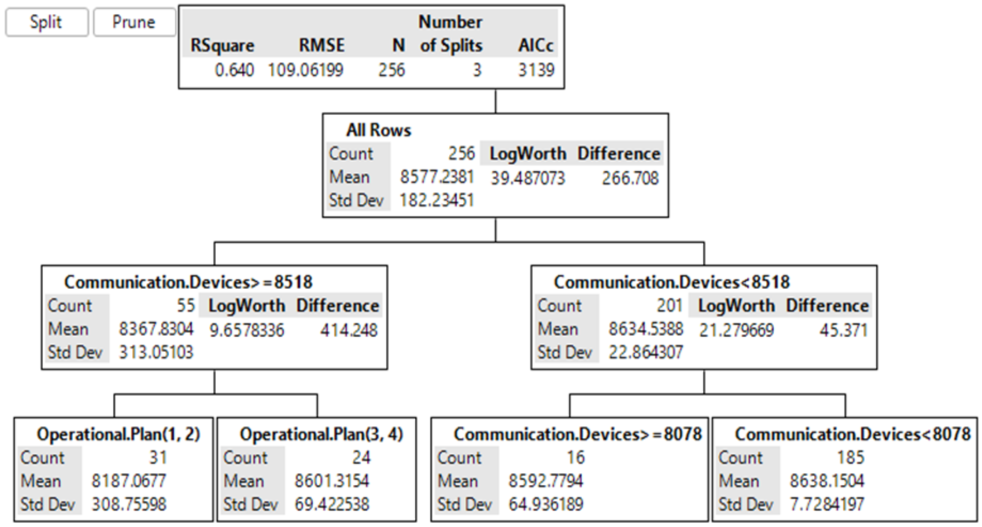


Figure 44. Partition Tree for Lower Bound Time Taken to Resupply 100% of Victim Clusters (Second Phase Experiment).

3. Fuel Efficiency of Each Capability Instantiation

The third MOE to be investigated is the fuel efficiency of each capability instantiation. Five partition trees were constructed, using: (1) fuel consumed, (2) fuel consumed per victim cluster resupplied, and the lower bound fuel consumed to resupply (3) 50%, (4) 75%, and (5) 100% of victim clusters, as the responses. The effects summary table for the lower bound fuel consumed to resupply 50/75/100% of victim clusters is shown in Table 16, with detailed explanation in Sections c, d, and e.

Table 16. Effects Summary Table for Partition Trees for Lower Bound Fuel Consumed to Resupply 50/75/100% of Victim Clusters (Second Phase Experiment)

Input Factors	**Lower Bound for Fuel Consumed to Resupply**		
	50% of Victims	**75% of victims**	**100% of Victims**
Operational Plan	-	√	√
Reduce Idle Time	√	-	-
Fuel Efficiency	√	√	√
Communication Devices	√	√	-
R^2 of Partition Tree	**0.61**	**0.77**	**0.87**

a. Fuel Consumed

Both "Operational Plan" and "Fuel Efficiency" factors have a large effect on the amount of fuel consumed. As shown in the partition tree in Figure 45, the first split is on the "Operational Plan" factor, and the second split is on the "Fuel Efficiency" factor. This finding shows that the shorter and faster DDT convoys (13,660 gallons) consumed approximately 2.3 times more fuel than longer and slower DDT convoys (5,903 gallons), presumably because collectively, they covered more distance and consumed fuel at a quicker rate. However, by improving on the fuel efficiency of the MTVRs (≥ 4.26), the shorter and faster DDT convoys can reduce their fuel consumption.

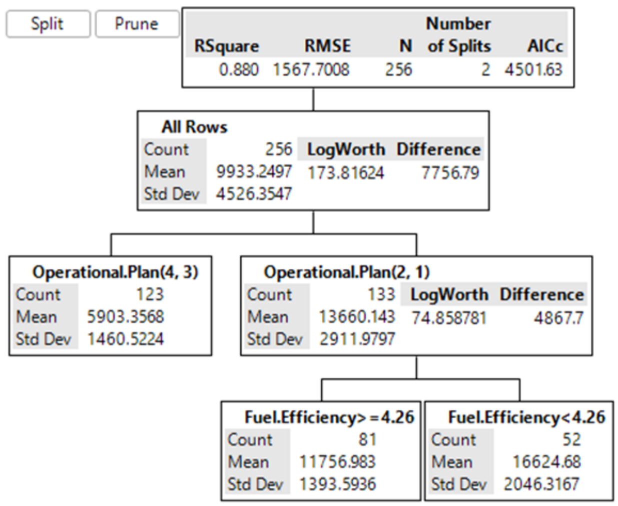


Figure 45. Partition Tree for Fuel Consumed (Second Phase Experiment).

b. Fuel Consumed Per Victim Cluster Resupplied

Similarly, both "Operational Plan" and "Fuel Efficiency" factors have a large effect on the amount of fuel consumed per victim cluster resupplied. As shown in the partition tree in Figure 46, the first split is on the "Operational Plan" factor, and the second and third splits are on the "Fuel Efficiency" factor. This finding shows that the shorter and faster DDT convoys (159 gallons) consumed approximately two times more fuel than longer and slower DDT convoys (81 gallons) per victim cluster resupplied. It was also observed that as a whole, longer and slower DDT convoys with worse fuel efficiencies (less than 3.93) consumed less fuel (101 gallons vs. 138 gallons) as compared to shorter and faster DDT convoys with better fuel efficiencies (≥ 4.28) per victim cluster resupplied.

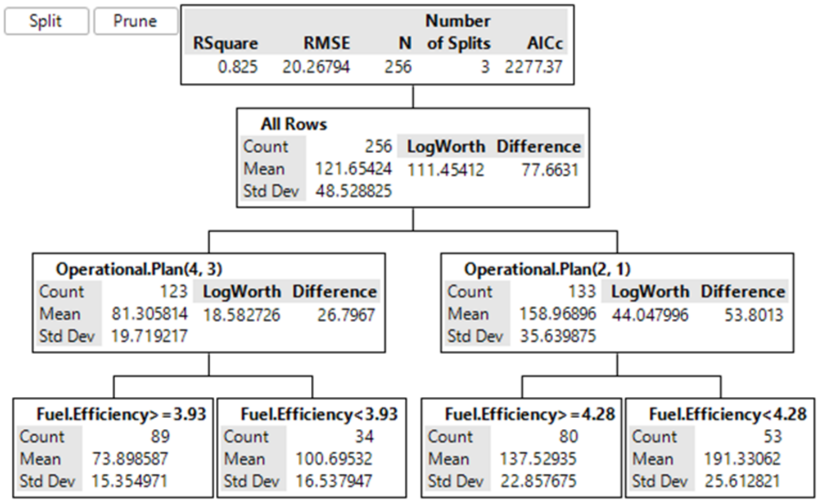


Figure 46. Partition Tree for Fuel Consumed Per Victim Cluster Resupplied (Second Phase Experiment).

c. Lower Bound for Fuel Consumed to Resupply 50% of Victim Clusters

The “Fuel Efficiency,” “Communication Devices,” and “Reduce Idle Time” factors have a large effect on the lower bound fuel consumed to resupply 50% of victim clusters. As shown in the partition tree in **Error! Reference source not found.**, the first split is on the “Fuel Efficiency” factor, and the second and third splits are on the “Communication Devices” factor. This finding shows that fuel efficient MTVRs (≥ 4.31) that are able to communicate with one another over relatively long distances (≥ 3,824 meters) and reduced idling time when resupplying victim clusters consume the least fuel (2,078 gallons), presumably because the DDT convoys do not have to travel unnecessarily searching for victim clusters to resupply them. On the other hand, DDT convoys that are only able to communicate with one another over short distances (lesser than 3,165 meters) consume the most fuel (3,387 gallons). For less fuel efficient MTVRs (less than 4.31), the amount of fuel consumed to resupply 50% of victim clusters is affected by the noise factors “Trafficability” and “Concealment.” As the “Operational Plan” factor does not appear in this partition tree, it suggests that all four operational plans considered in this thesis were able to resupply 50% of victim clusters equally well.

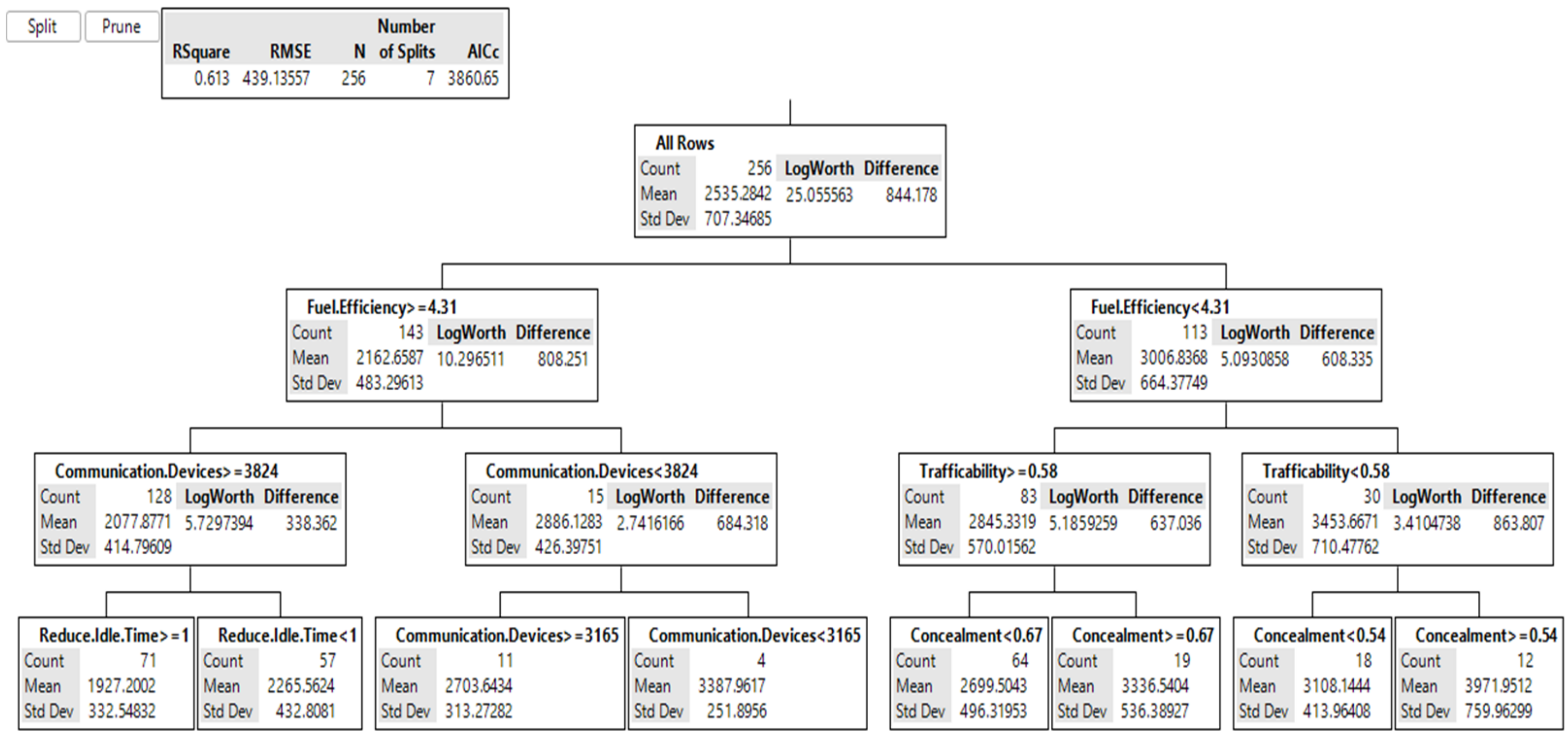


Figure 47. Partition Tree for Lower Bound Fuel Consumed to Resupply 50% of Victim Clusters (Second Phase Experiment)

d. Lower Bound for Fuel Consumed to Resupply 75% of Victim Clusters

The "Communication Devices," "Fuel Efficiency," and "Operational Plan" factors have the largest effect on the lower bound fuel consumed to resupply 75% of victim clusters. As shown in the partition tree in Figure 48, the first split was on the "Communication Devices" factor, while the second and third splits were on the "Fuel Efficiency" and "Operational Plan" factors respectively. The right hand of the partition tree suggests that when the DDT convoys are not able to communicate with one another over long distances (less than 4,729 meters), utilizing shorter and faster DDT convoys will lead to a greater amount of fuel consumed to resupply 75% of victim clusters, presumably because without effective communications, they are mostly operating as independent entities, driving around searching for victim clusters and consuming more fuel in the process.

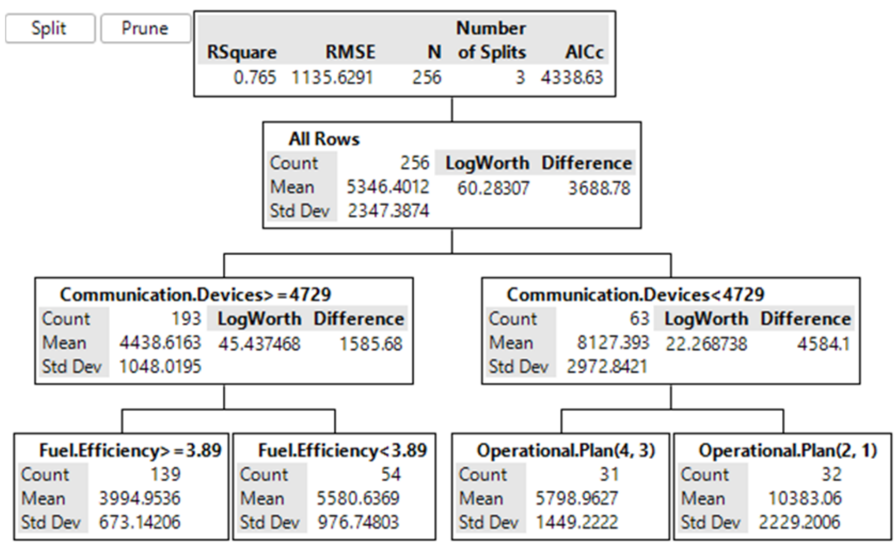


Figure 48. Partition Tree for Lower Bound Fuel Consumed to Resupply 75% of Victim Clusters (Second Phase Experiment).

e. Lower Bound for Fuel Consumed to Resupply 100% of Victim Clusters

The "Operational Plan" and "Fuel Efficiency" factors have the largest effect on the lower bound fuel consumed to resupply 100% of victim clusters. As shown in the partition tree in Figure 49, the first split was on the "Operational Plan" factor, and the second split was on the "Fuel Efficiency" factor. Subsequent splits in the partition tree were similar to the first two splits, alternating between the "Operational Plan" and "Fuel Efficiency" factors. The findings show that across the range, longer and slower DDT convoys consumed lesser fuel to resupply 100% of victim clusters as compared to shorter and faster DDT convoys.

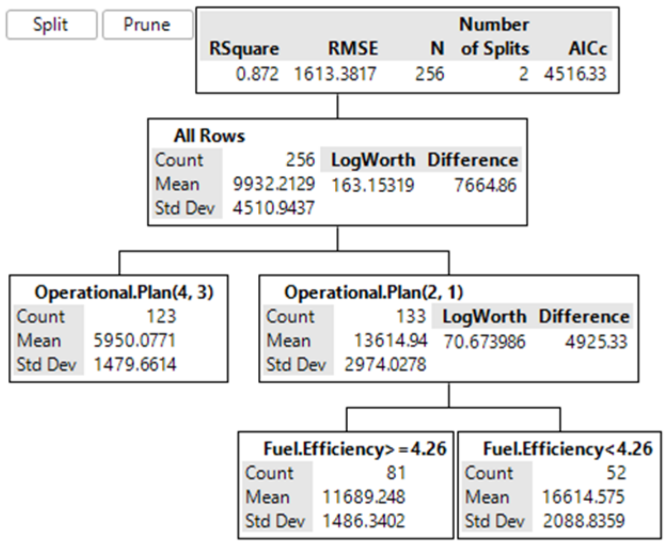


Figure 49. Partition Tree for Lower Bound Fuel Consumed to Resupply 100% of Victim Clusters (Second Phase Experiment).

4. Tradeoff Between Fuel Consumed and Timeliness in Delivering Supplies to Victim Clusters

To explore the tradeoff between MOE 2—time taken to resupply victim clusters and MOE 3—fuel efficiency of each capability instantiation, the amount of fuel consumed to resupply: (1) 50%, (2) 75%, and (3) 100% of victim clusters was plotted against the time taken to resupply its corresponding percentage of victim clusters.

a. Fuel Consumed vs. Time Taken to Resupply 50% of Victim Clusters

In Figure 50, we see that most runs are able to resupply 50% of victim clusters within 72 hours., as there were not many censored runs which lie on the end of simulation reference line. In particular, we observe that when holding the lower bound on fuel constant at low levels (e.g., 5,000 gallons), the runs corresponding to operational plans that utilized shorter and faster DDT convoys were able to resupply 50% of victim clusters the quickest, while the runs corresponding to operational plans that utilized longer and slower DDT convoys were slower at resupplying 50% of victim clusters. In addition, we notice at the top right area of the graph that there are instances where operational plans that utilized shorter and faster DDT convoys consumed more fuel than operational plans that utilized longer and slower DDT convoys

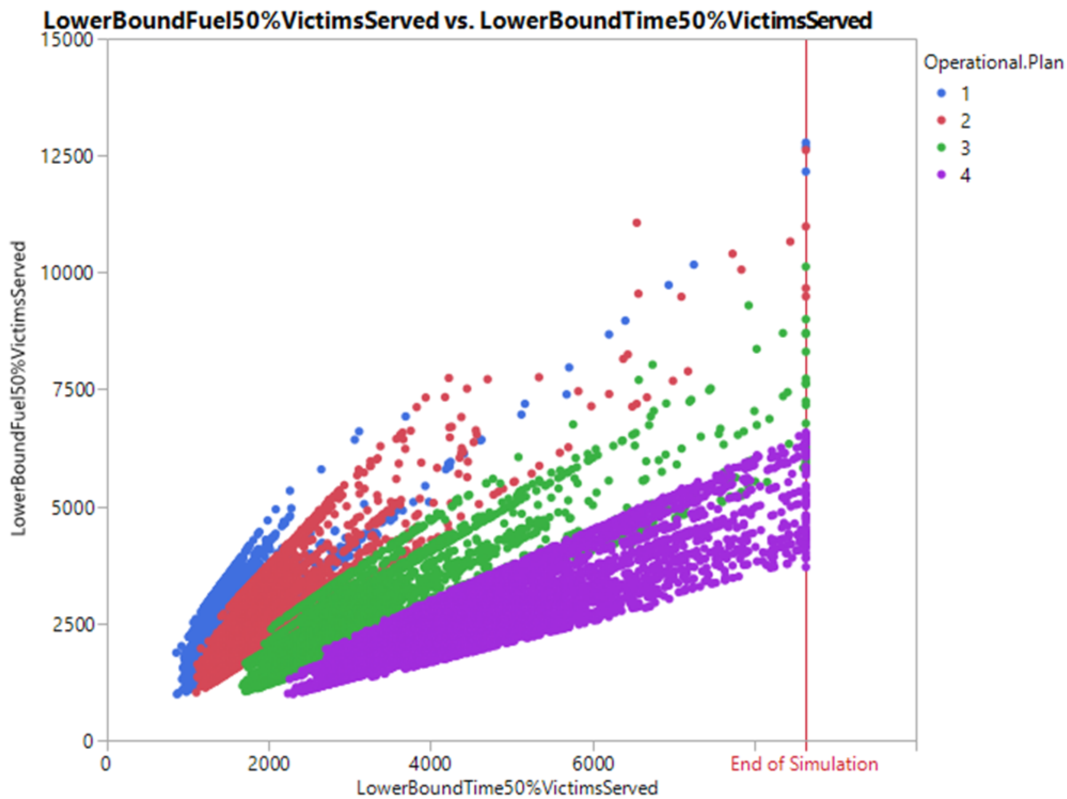


Figure 50. Graph for Fuel Consumed vs. Time Taken to Resupply 50% of Victim Clusters (Second Phase Experiment).

b. Fuel Consumed vs. Time Taken to Resupply 75% of Victim Clusters

In Figure 51, we see that there are more censored runs that lie on the end of simulation reference line, indicating that there are lesser runs that are able to resupply 75% of victim clusters within 72 hours. In particular, we observe that most runs corresponding to operational plans that utilized shorter and faster DDT convoys were able to resupply 75% of victim clusters the quickest, but the runs corresponding to these operational plans also consumed more fuel, as shown by the different layers in the graph, with operational plan 1 consuming the most fuel and operational plan 4 consuming the least fuel.

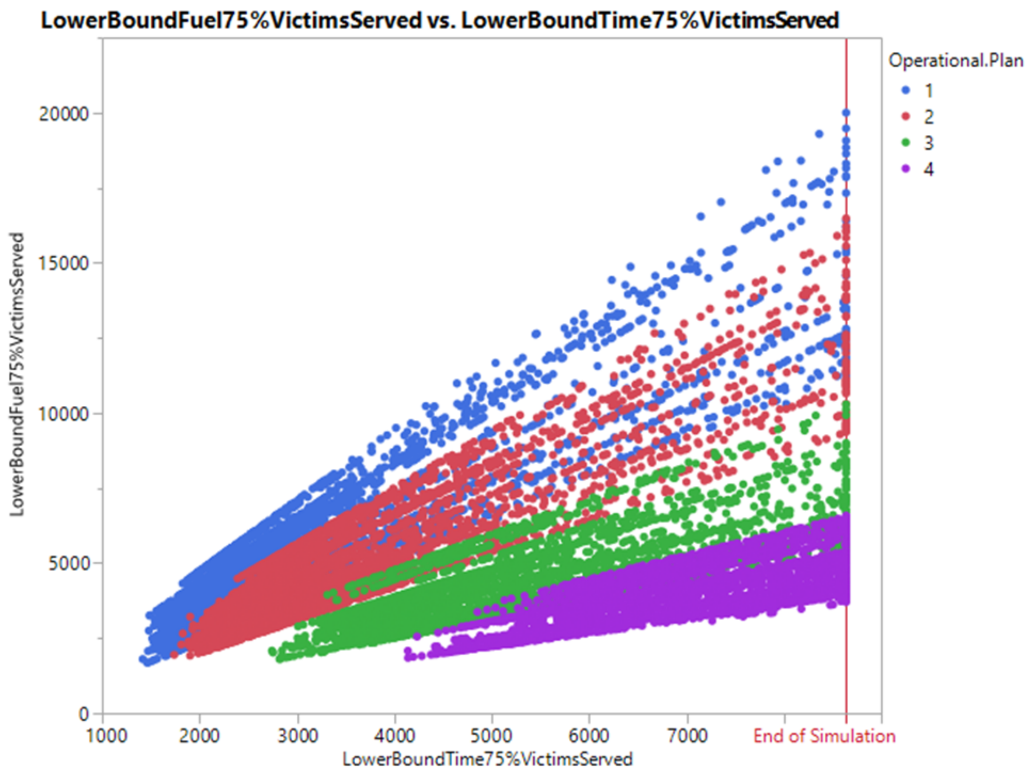


Figure 51. Graph for Fuel Consumed vs. Time Taken to Resupply 75% of Victim Clusters (Second Phase Experiment).

c. Fuel Consumed vs. Time Taken to Resupply 100% of Victim Clusters

In Figure 52, we see that there are many censored runs that lie on the end of simulation reference line, indicating that they are unable to resupply 100% of victim clusters within 72 hours. For the runs that are able to do so, we observe that runs corresponding to operational plans that utilize shorter and faster DDT convoys consume more fuel than runs corresponding to operational plans that utilize longer and slower DDT convoys, albeit that some of the runs in the former are able to resupply 100% of victim clusters quicker than the latter. Operational plan 4 was never observed to resupply 100% of victim clusters within 72 hours, regardless of the values of the other factors.

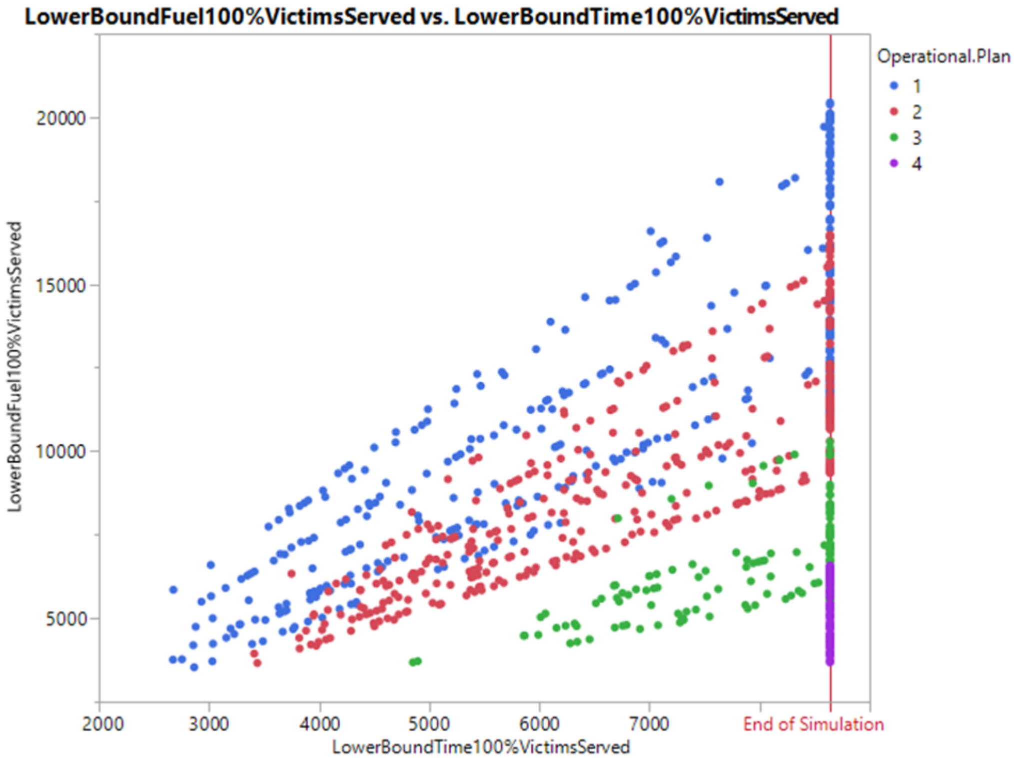


Figure 52. Graph for Fuel Consumed vs. Time Taken to Resupply 100% of Victim Clusters (Second Phase Experiment)

VI. CONCLUSIONS

The aim of this thesis was to study the effect of several OE-focused enhancements in extending the operational reach of a MEU in a HADR mission. This chapter restates the research questions originally listed in Chapter I, Section F, and provides insights that directly answer the questions.

A. ANALYTICAL INSIGHTS

The research questions and their respective insights are presented here.

1. What Is the Effectiveness of Current MEU Assets Supporting HADR Resupply Operations in Terms of Throughput of Resources?

The research shows that current MEU assets are able to support HADR resupply operations, but with a varying degree of success depending on the specific operational plan utilized as well as the "noise" factors examined in this thesis. This is evident in the wide range of number of victims resupplied, which ranged from a minimum of 12 to a maximum of 100 (Figure 24.). The effectiveness depends on the operational plan employed by the MEU commander and the use of communication devices between the DDT convoys. If the MEU commander is restricted to the four operational plans studied, he or she should utilize operational plans consisting of shorter and more numerous DDT convoys that are able to travel independently, and at higher speed. Since DDT convoys are able to operate independently from each other, the use of communication devices allows them to quickly develop an operational picture of the HADR "battlespace." As a result, the DDT convoys are able to spend less time searching for isolated victims; rather, they are able to use the time saved to deliver relief supplies to a greater number of victims.

2. How Do the Energy Requirements of Current MEU Assets Supporting HADR Resupply Operations Limit its Capability to Maximize Delivery of Resources to Disaster Areas?

Not surprisingly, the research shows that the "Fuel Efficiency" factor has a strong influence on all the MOPs associated with the MOE of fuel efficiency of each capability instantiation. From Chapter V, Section A.8, the approximate amount of fuel consumed by a fleet of 30 MTVRs conducting HADR resupply operations over three days ranged from 3,687 gallons to 20,076 gallons. According to the Center of Naval Analyses, the daily fuel requirement for the MEU ground combat element (GCE) is 6,546 gallons based on assault requirements (Table 17); assault requirements are used because they are similar to the first 72 hours of the ground resupply effort studied in this thesis. Hence, the total amount of fuel that is allocated to the GCE for three days of operations is 19,638 gallons, and the fuel consumed by the HADR resupply operation represents 18.77% to 102.23% of the total three-day quota. It is likely that the energy requirement of the MTVRs conducting HADR resupply operations may hamper its capability to maximize delivery of resources to disaster areas, and MEU commanders may have to reallocate fuel designated for other elements, such as the air combat element (ACE) or the MEU service support group (MSSG) to support the HADR resupply operation.

Table 17. Daily Fuel Requirement for MEU. Adapted from Webb (2006, II-52).

	Baseline MEU	
	Assault (Gals/24 hrs)	Sustained (Gals/24 hrs)
CE	640	325
GCE	6,546	3,610
ACE	50,508	49,557
MSSG	1,854	1,524
TOTAL	**59,548**	**55,016**

In terms of fuel consumed per victim cluster resupplied, analysis indicates that longer convoys traveling at slower speed perform better than smaller convoys traveling at higher speed (i.e., longer convoys are able to resupply more victim clusters per unit fuel consumed). Should energy sources be limited, one possibility is to deploy longer and slower convoys for HADR resupply missions to conserve energy. Alternatively, the tradeoff analysis indicates that shorter and faster convoys can also be utilized, albeit for a shorter period of time.

3. How Do OE Considerations Influence the Resupply Options of a MEU Conducting HADR Resupply Operations?

Generally, most of the OE-focused assets and policies tested via the MANA simulation had a positive effect on the MOEs, and should be considered for future implementation to extend operational reach. Although not an OE consideration, a general insight gleaned from the research indicates that the "Operational Plan" factor has a strong influence on the MOEs and MOPs as it was present in all of the partition tree models. Hence, MEU commanders are recommended to place more emphasis on the operational plans considered for employment in a HADR resupply mission, in order to ensure greater probability of mission success.

Conversely, it was observed that the "Reduce Idle Time" factor only had a limited effect on the MOEs relative to the other factors. This may be because it only affects the situation when the DDT convoys are resupplying victims. The relatively short time span of 0.5 hours to resupply a victim cluster means that the "Reduce Idle Time" factor was not able to significantly affect any of the MOEs. Nonetheless, it directly saves a small amount of fuel. A suggested improvement is to allow the "Reduce Idle Time" factor to also affect the situation when the DDT convoys are being restocked at the LDC, or to insert a penalty for vehicle idling before moving out from a LDC to account for PCCs; these practices are prohibited but still commonly practiced in reality (Peters 2016).

4. What OE-focused Assets and Policies Should a MEU Include in Its Resupply System to Improve Its Throughput of Resources to Disaster Areas?

This research reveals that the "Fuel Efficiency" factor had a significant effect on MOE 3 (fuel efficiency of each capability instantiation). Hence, the OE-focused assets and policies that the MEU should include in its resupply system should be those that pertain to the "Fuel Efficiency" factor, such as: (1) employing trained drivers, (2) employing hybrid technologies, and (3) employing follower vehicle technologies.

B. LIMITATIONS

A limitation of using MANA as the choice of simulation software in this thesis is that MANA is only able to have one "ammunition" counter to account for a variety of relief supplies. For scenarios that involve several resupply items, it would be better to consider other simulation software such as Pythagoras, which is able to account for four different types of supplies. In addition, MANA has no predefined function for the act of resupply, so certain workarounds had to be performed in order to implement the scenario in MANA.

C. FOLLOW-ON WORK

Due to security concerns, the MANA model was constructed using open source and unclassified material. Future work could improve upon the fidelity of the model by incorporating additional information obtained from the DOD, defense agencies and contractors, or other classified sources.

Sources of information notwithstanding, the MANA model developed in this thesis could also be used to explore the implementation of breaking-edge capabilities and technologies in HADR operations to extend operational reach, such as foraging techniques, water purification capabilities, unmanned technologies, and solar power. By changing the terrain and background map, and adjusting for specific differences, the MANA model could also be adapted to explore other operational scenarios such as Operation UNIFIED RESPONSE and Operation SEA ANGEL II.

Lastly, future experiments could explore variations to the "Operational Plan" factor, since it was identified as one of the most dominant factors. For example, the linear relationship between convoy size and speed can be relaxed to allow for shorter and slower convoys, as well as longer and faster convoys.

APPENDIX. DDT PRE-PLANNED ROUTES

This appendix contains the six pre-planned routes on which the MEU commander may choose to deploy the DDT convoys in this thesis (Figures 52 to 57).

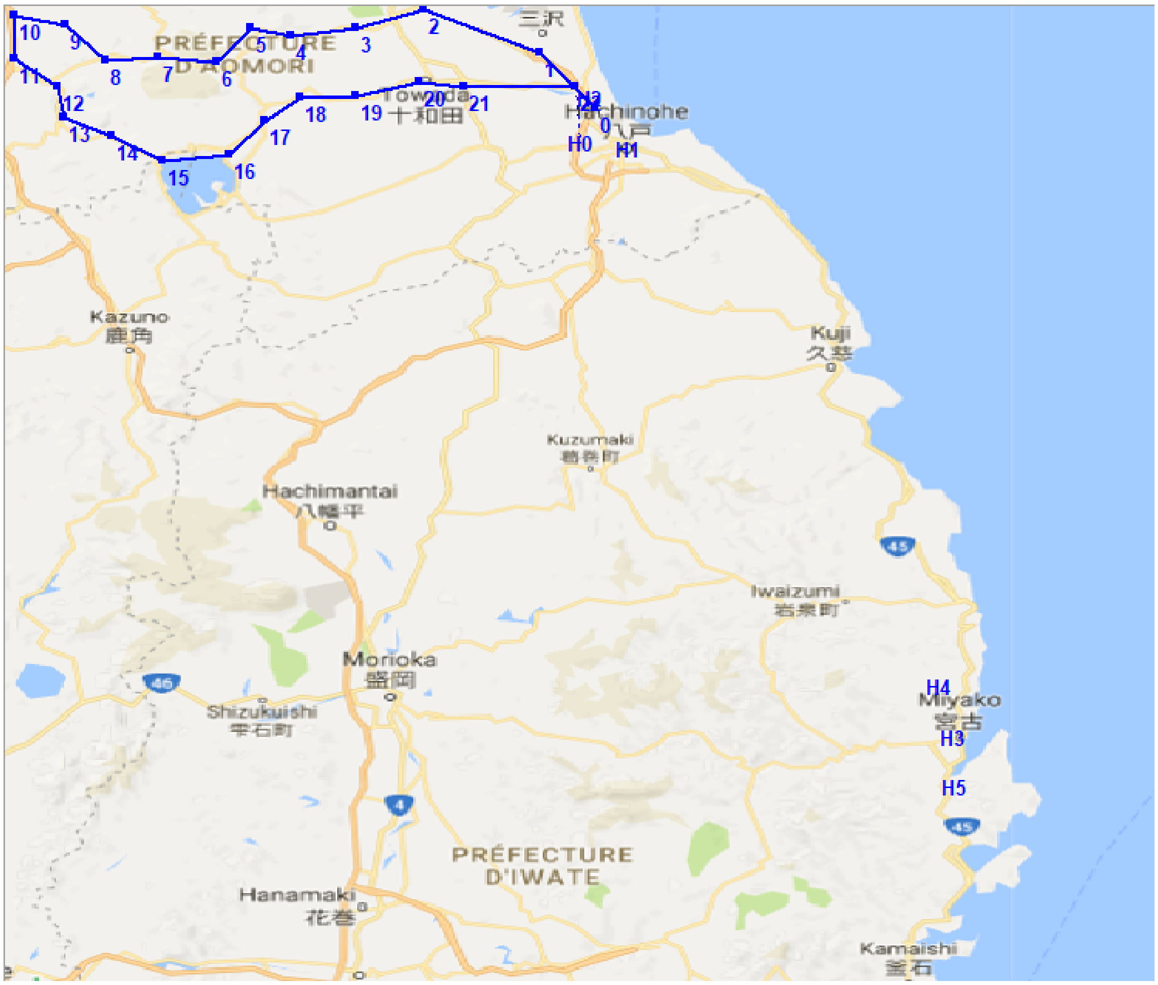


Figure 53. Pre-planned Route 1. Adapted from Google Maps.

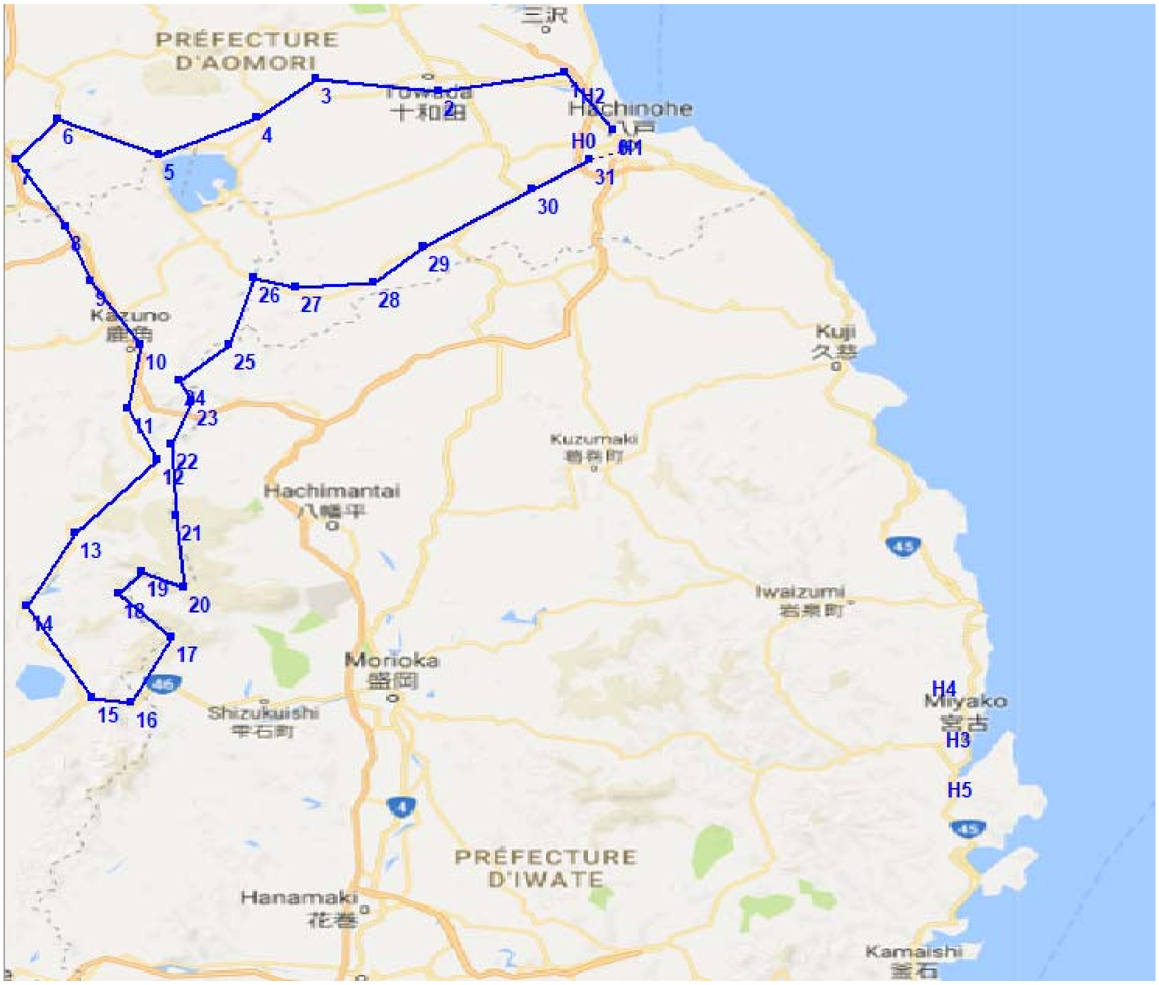


Figure 54. Pre-planned Route 2. Adapted from Google Maps.

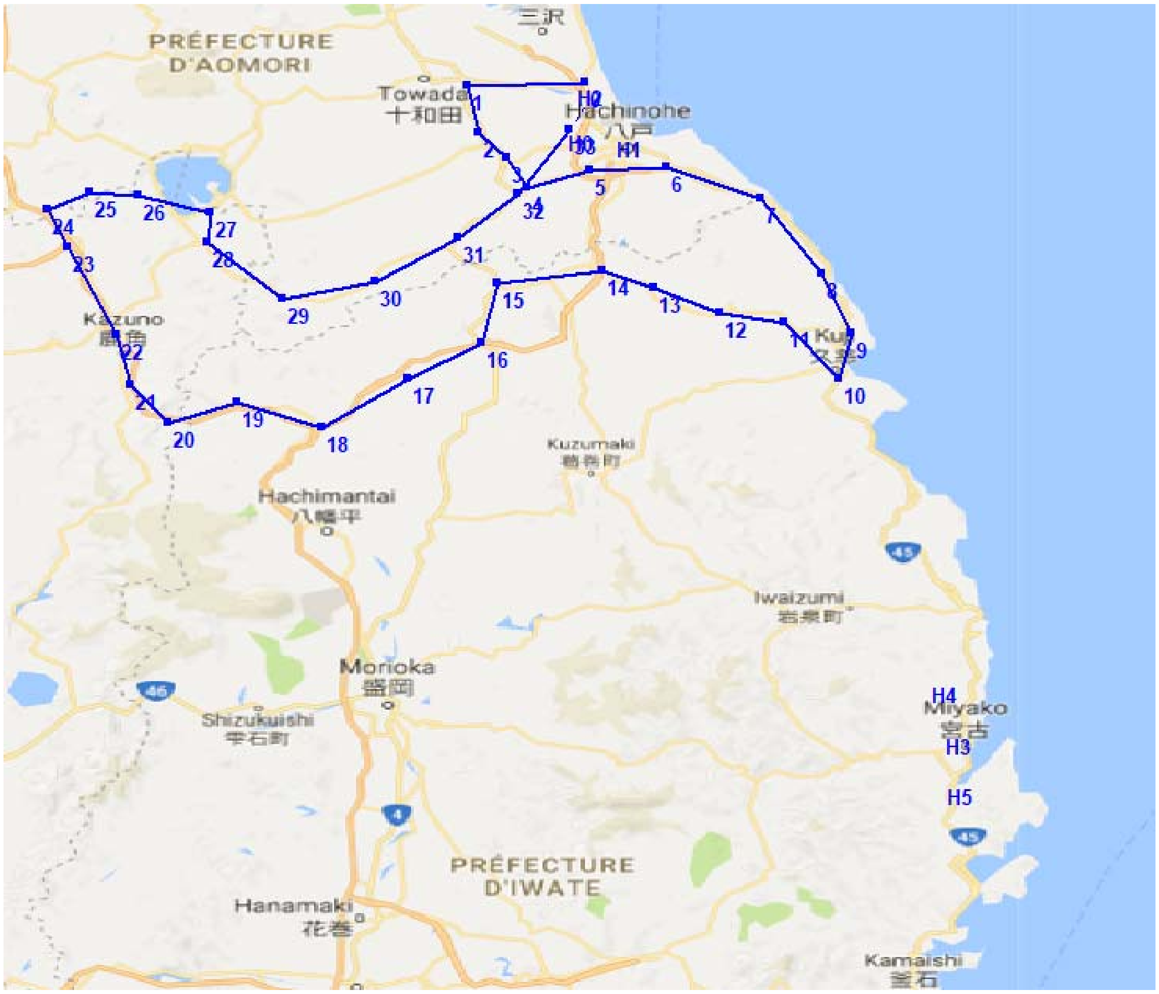


Figure 55. Pre-planned Route 3. Adapted from Google Maps.

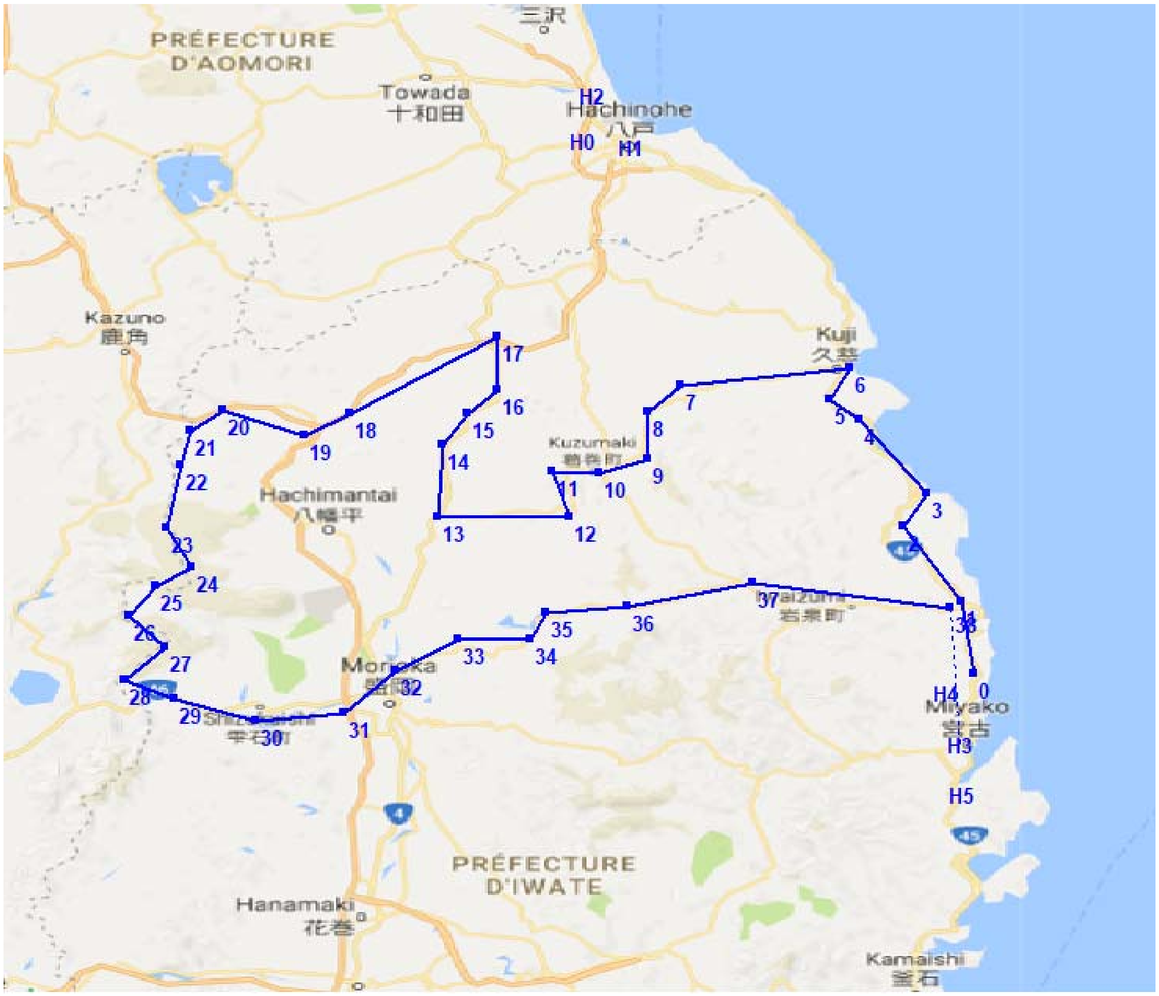


Figure 56. Pre-planned Route 4. Adapted from Google Maps.

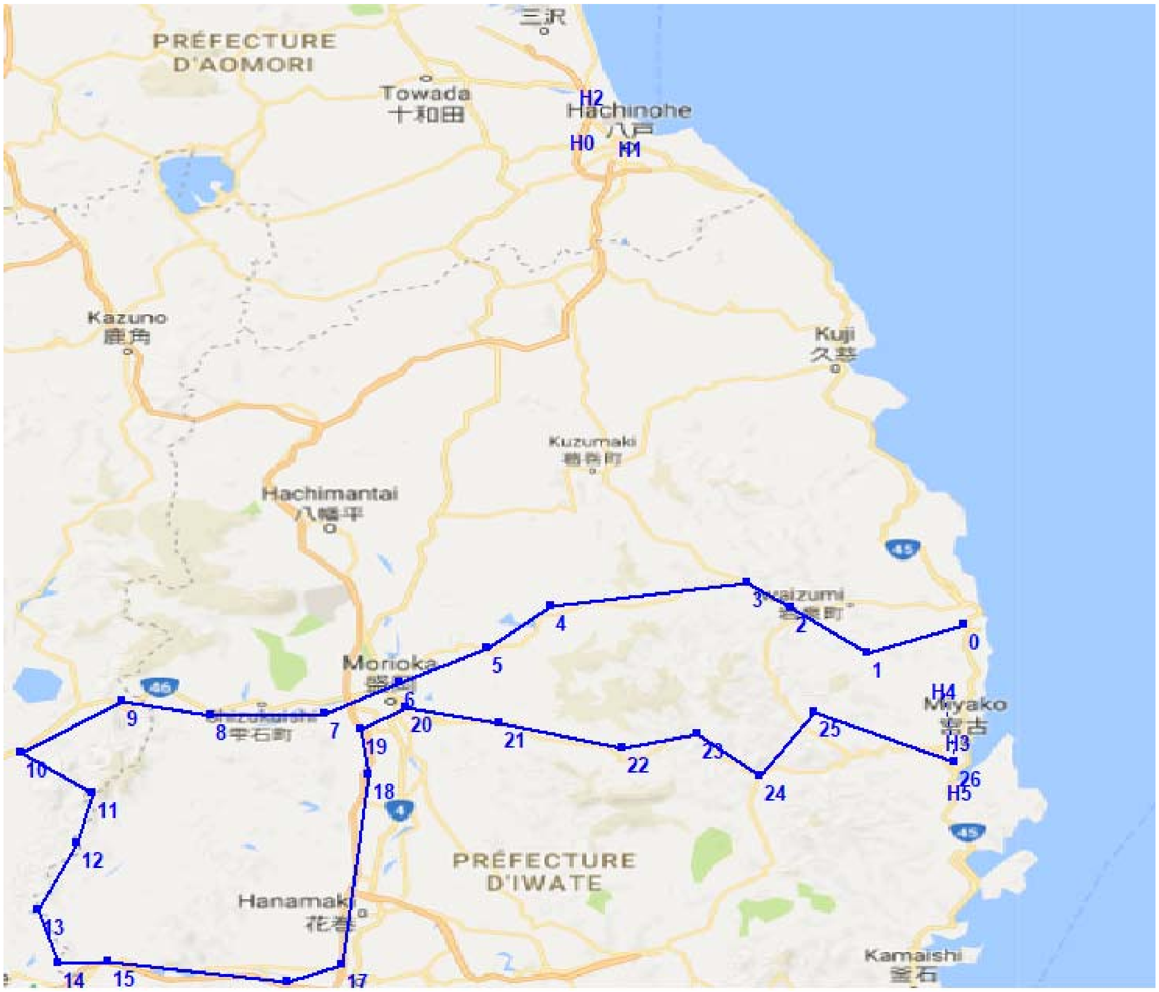


Figure 57. Pre-planned Route 5. Adapted from Google Maps.

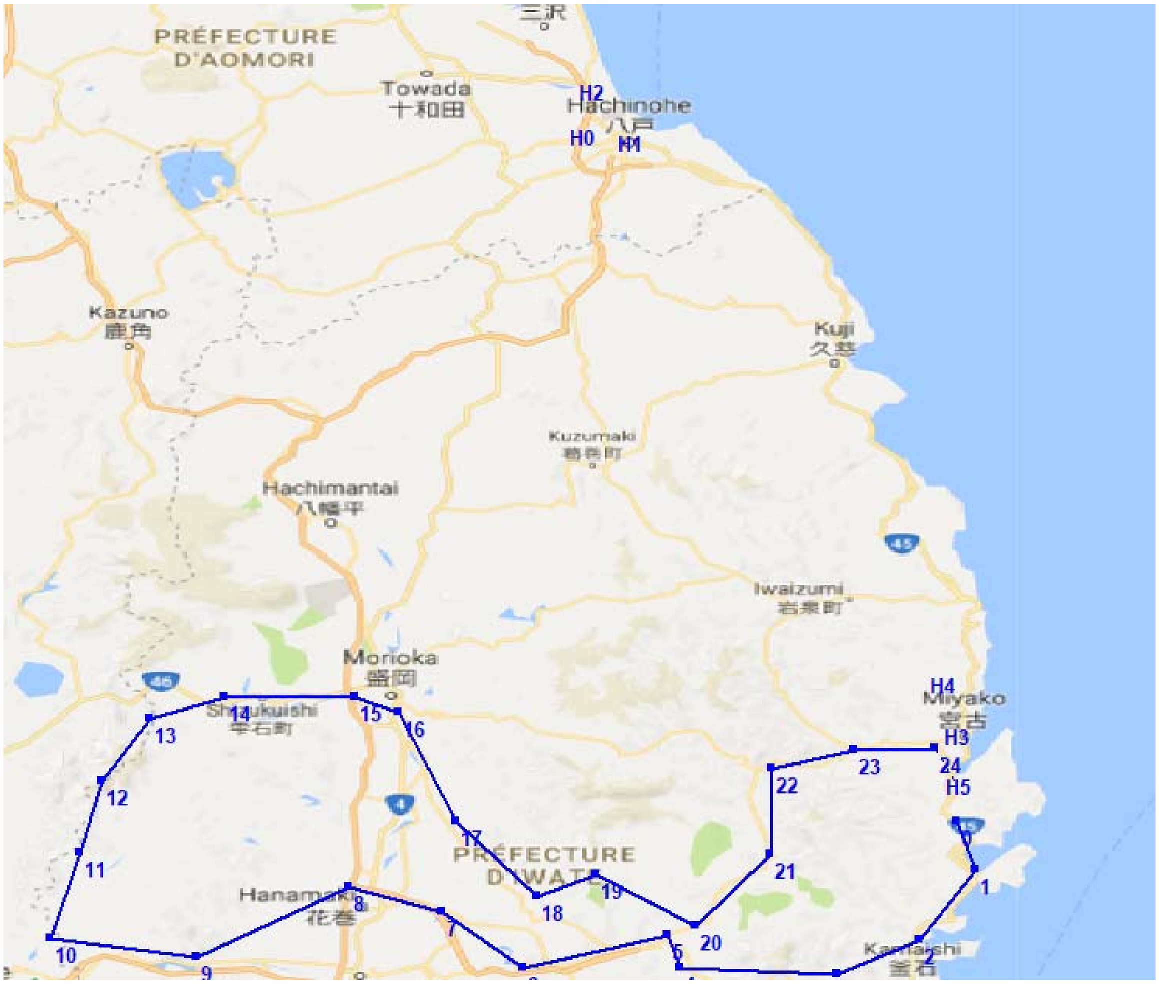


Figure 58. Pre-planned Route 6. Adapted from Google Maps.

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